MEASUREMENT AND PREDICTION OF STAGE AND DISCHARGE WITH GROUND-BASED IMAGERY

A DISSERTATION
Presented to the Faculty of
The School of Natural Resources at the
University of Nebraska

In Partial Fulfillment of Requirements
For the Degree of Doctor of Philosophy

Major: Natural Resource Sciences

Kenneth Wayne Chapman ~ June 8, 2023

Supervisory Committee

Troy E. Gilmore, PhD, Committee Member, Chair

Aaron R. Mittlestet, PhD, Committee Member, Reader

Mary J. Harner, PhD, Outside Member, Reader

Mehrube Mehrubeoglu, PhD, Special Member

Andrew Harms, PhD, Committee Member

State of Nebraska bona fides

Grandfather, Otis Chapman, born in Madison, NE – 1893

Grandmother, Ethyl Chapman, born in Lynch, NE – 1898

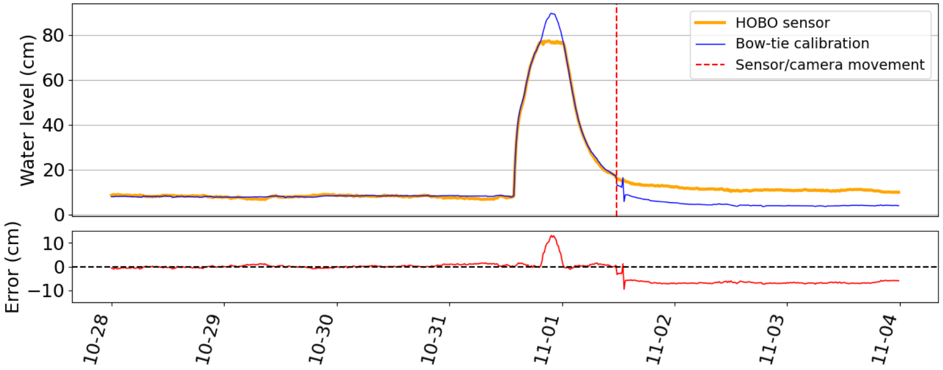
Agenda

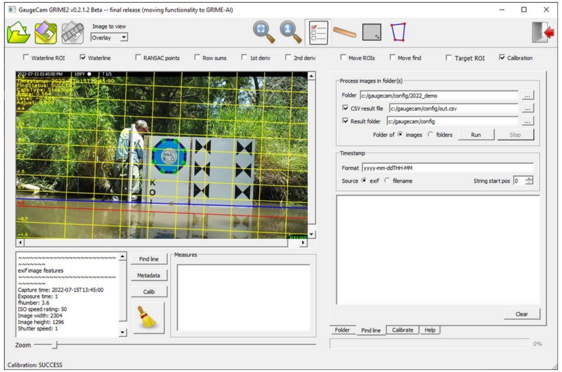
1) Background
2) Studies
   A) GRIME2 software package
   B) GRIME2 target improvement
   C) Stage and discharge from documentary time-lapse imagery
3) Conclusions and future research
4) Acknowledgments
5) Questions

Background—Motivation

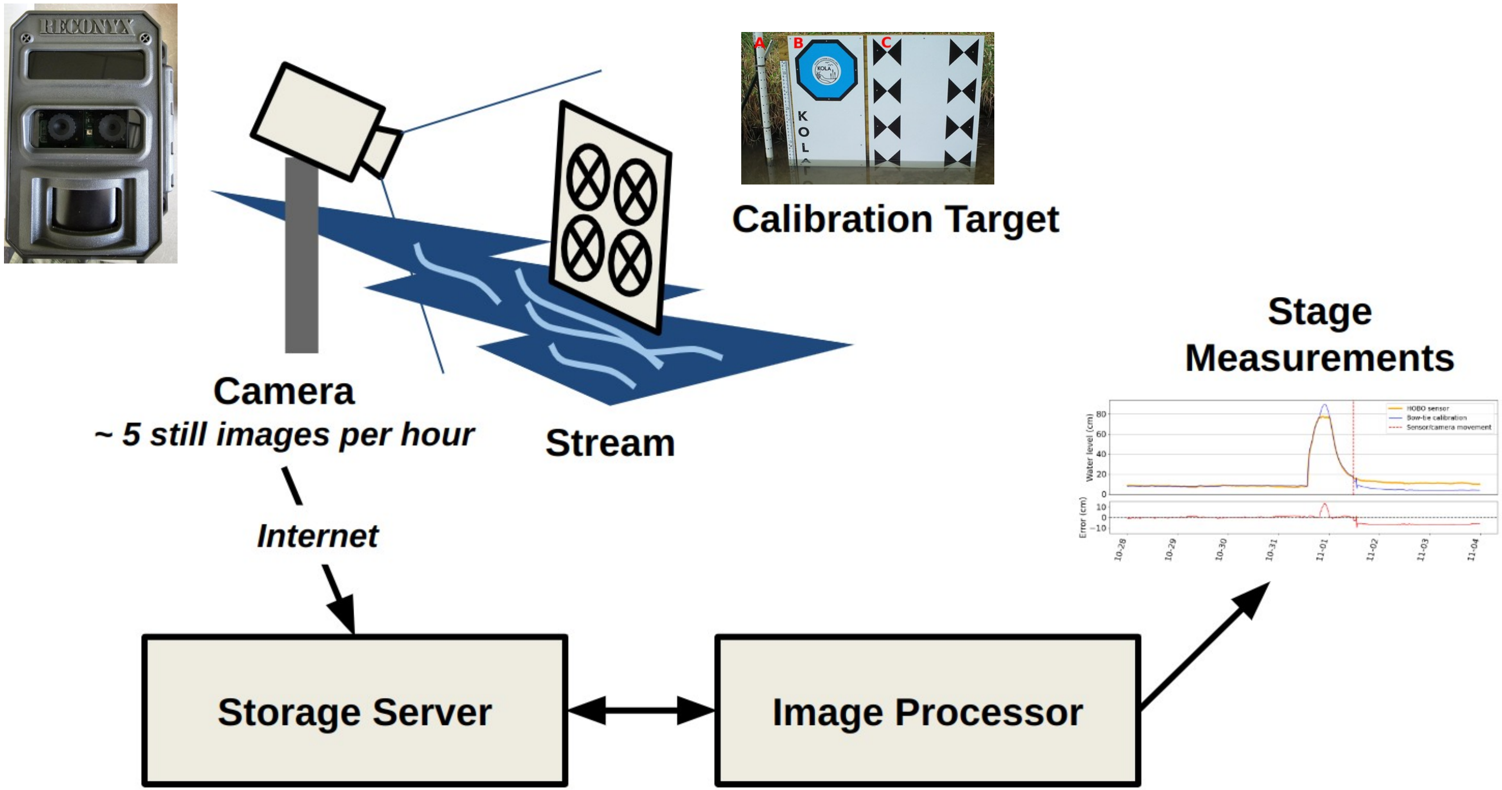
- **Need complete records of stage (water level) and discharge (streamflow)**
  - **Water distribution policy, discharge calculation, navigation and recreational use planning, flood management, wildlife habitat, etc.**

- **Develop image processing tools to measure and estimate stage and discharge from images**
  - **Corroborates existing records**
  - **Fills gaps when other equipment fails**
  - **Imagery includes additional contextual information**



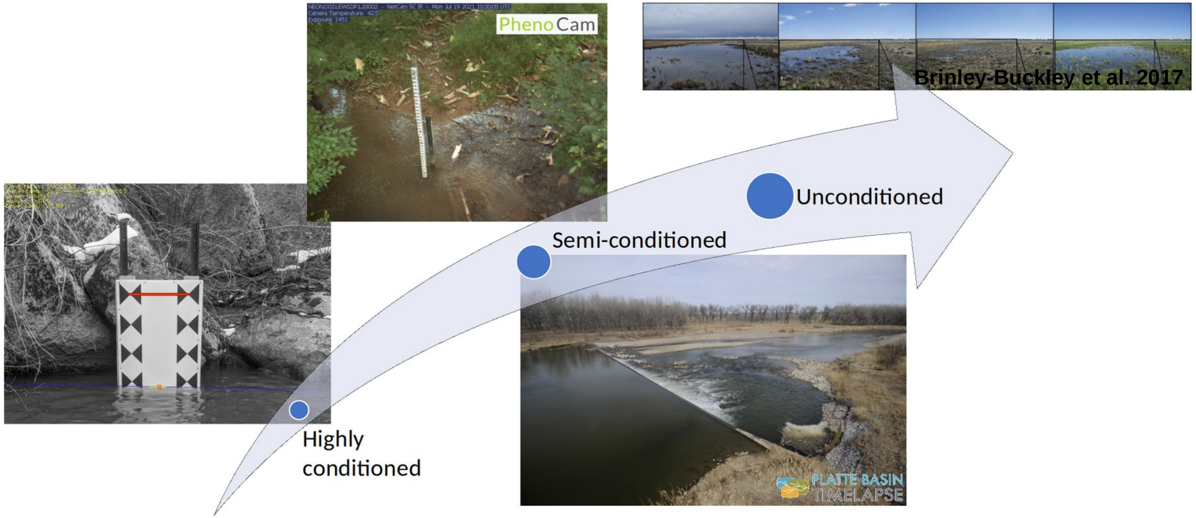


Background—Image-based Stage Measurement System



Research Problem—Image Conditioning Level

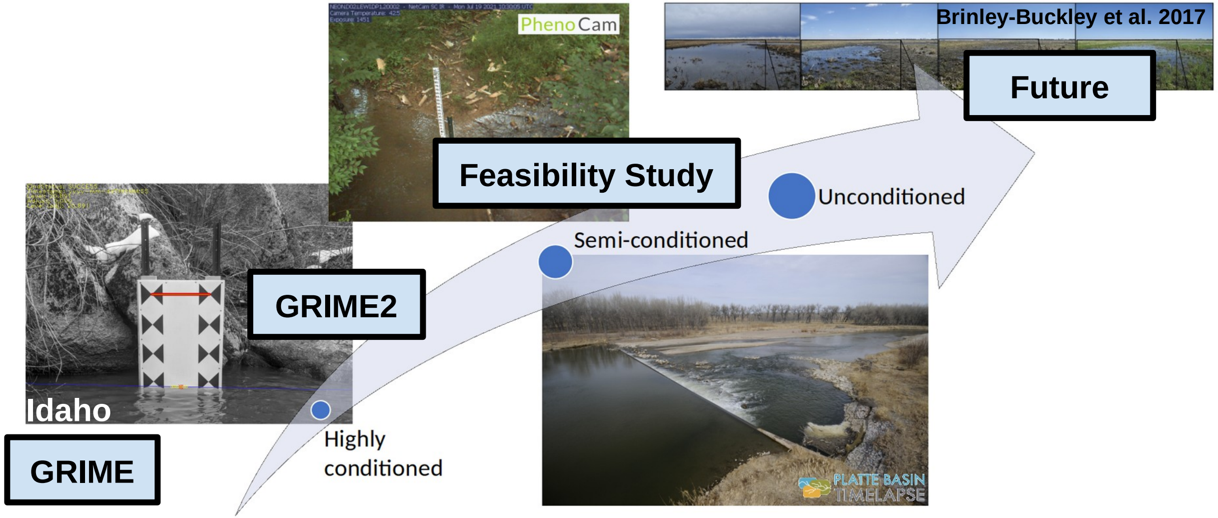
- How much is the scene controlled to facilitate image processing?



Research Problem—Image Conditioning Level

- **Image conditioning level influences image processing approach**
  - **Less conditioning = fewer control features available to imaging algorithm**

- **Focus on highly and semi-conditioned problems**
  - **Paves way toward solutions to unconditioned problems**



Background—Image Repositories

Research sites

- Possible to design conditioning

- Kearney Outdoor Learning Area
- UNL Gudmundsen Sandhills Laboratory
- KU Burgin Lab Research Sites

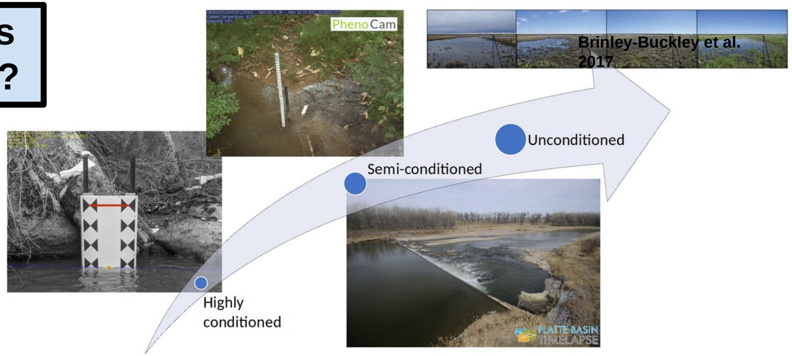
- Evolve current highly-conditioned measurement techniques

Existing image repositories

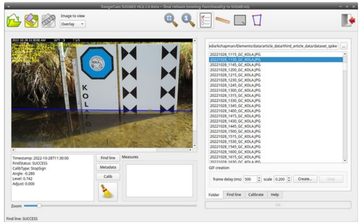
- Little or no conditioning

- NSF Neon
- NAU Phenocam
- UNL Platte Basin Timelapse Project
- USGS HiVis

- Is there enough information in the images to measure or predict stage or discharge?



Background—Objectives for GRIME2



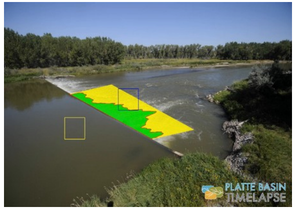
Create a free, open-source stage measurement system usable by all hydrologists and ecologists

Create professional-grade stage measurement package

Reduce target footprint

Develop measurement capability for images with less conditioning while maintaining precision

- Increase ease of use in conditioned scenes
- Determine whether measurement is possible with less image conditioning



Study information content of semi-conditioned images

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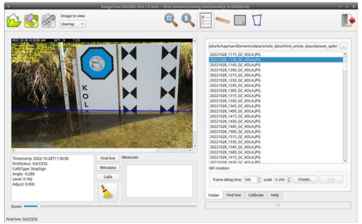
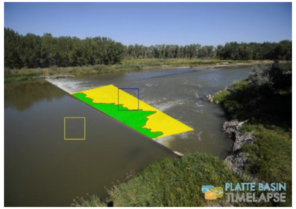


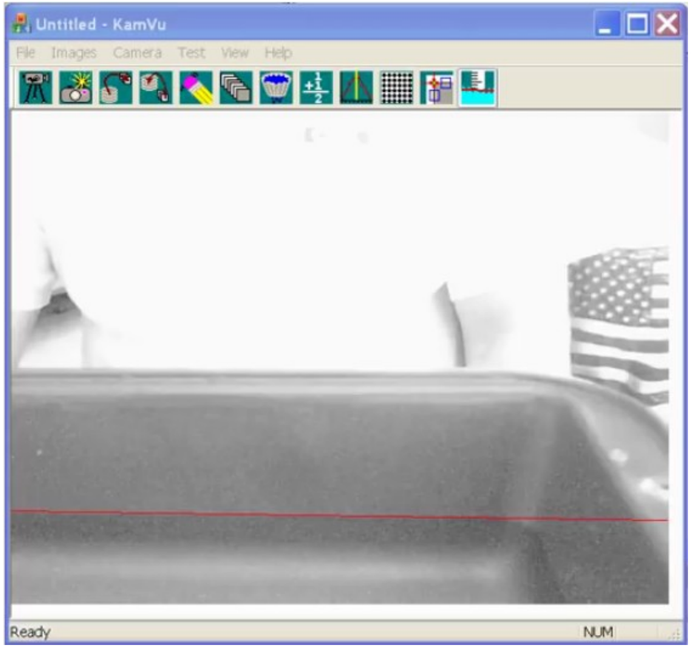
Create professional-grade stage measurement package

Reduce target footprint



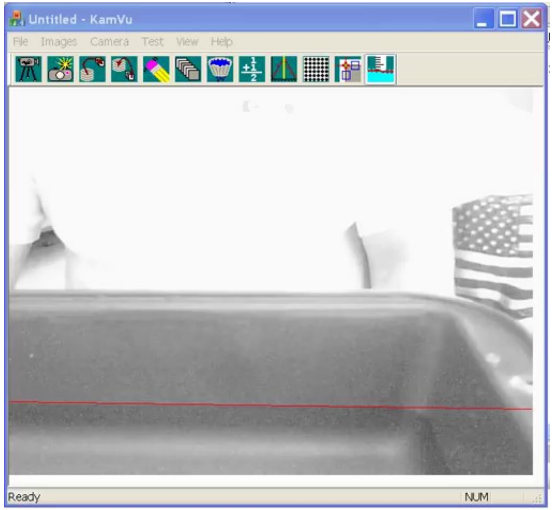
Study information content of semi-conditioned images

Studies—First Try



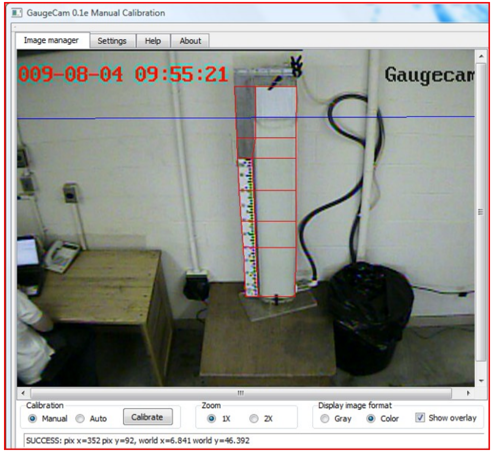
2009 bread pan experiment on the desktop

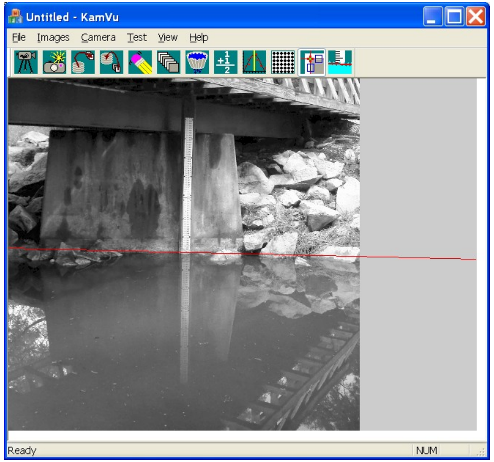
Studies—First Try



2009 bread pan experiment on the desktop

Studies—GRIME before UNL



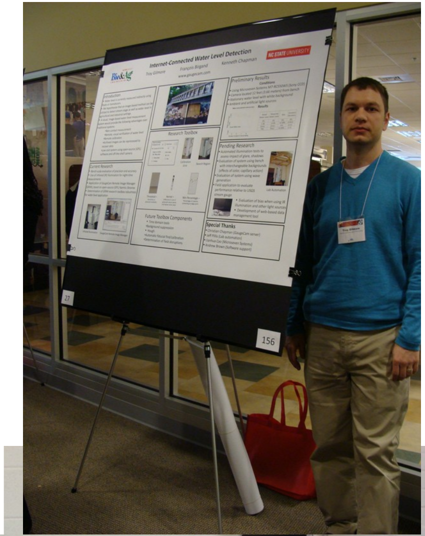


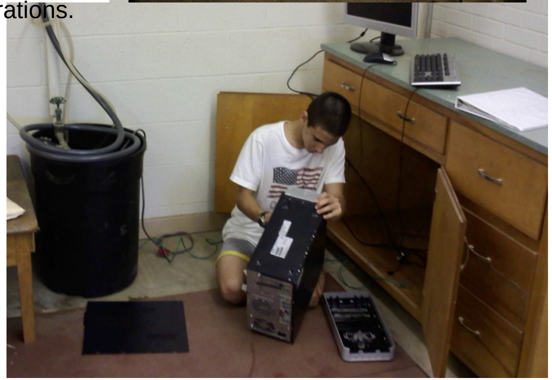
Research completed prior to arrival at University of Nebraska - Lincoln

- Troy E. Gilmore, François Birgand, and Kenneth W. Chapman. Source and magnitude of error in an inexpensive image-based water level measurement system. Journal of Hydrology, 496(2013):178–186, 2013.

- F Birgand, K. W. Chapman, A. Hazra, T. E. Gilmore, J. R. Etheridge, and A-M Staicu. Field performance of the gaugecam image-based water level measurement system. PLOS Water, 1(7), 2022.

- J. R. Etheridge, F. Birgand, and M. R. Burchell II. Quantifying nutrient and suspended solids fluxes in a constructed tidal marsh following rainfall: The value of capturing the rapid changes in flow and concentrations.

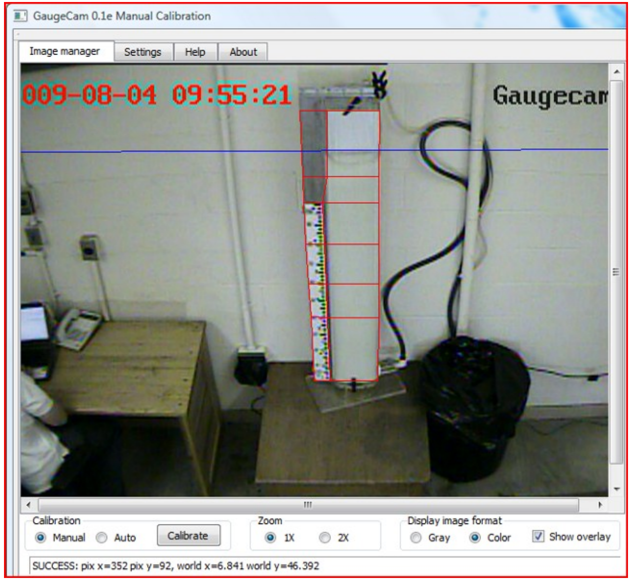




Shortcomings of GRIME

- **Difficult to install and use**
  - **Demands manual input of calibration coordinates**
  - **No serialization of calibrations and setup files**
  - **No batch tools to evaluate large repositories of images**

- **Fragile measurement algorithm**
  - **Sensitive to typical scene variations:**
    clouds, glint, nighttime, etc.
  - **Sensitive to camera movement**
  - **Sensitive to non-linearity in calibration points**
  - **Many bugs…**



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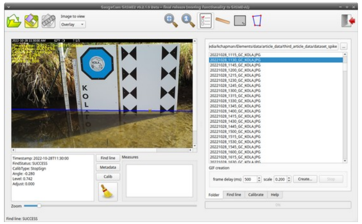
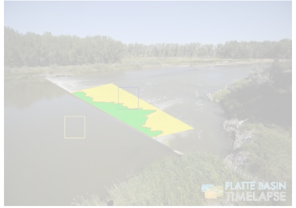


Create professional-grade stage measurement package

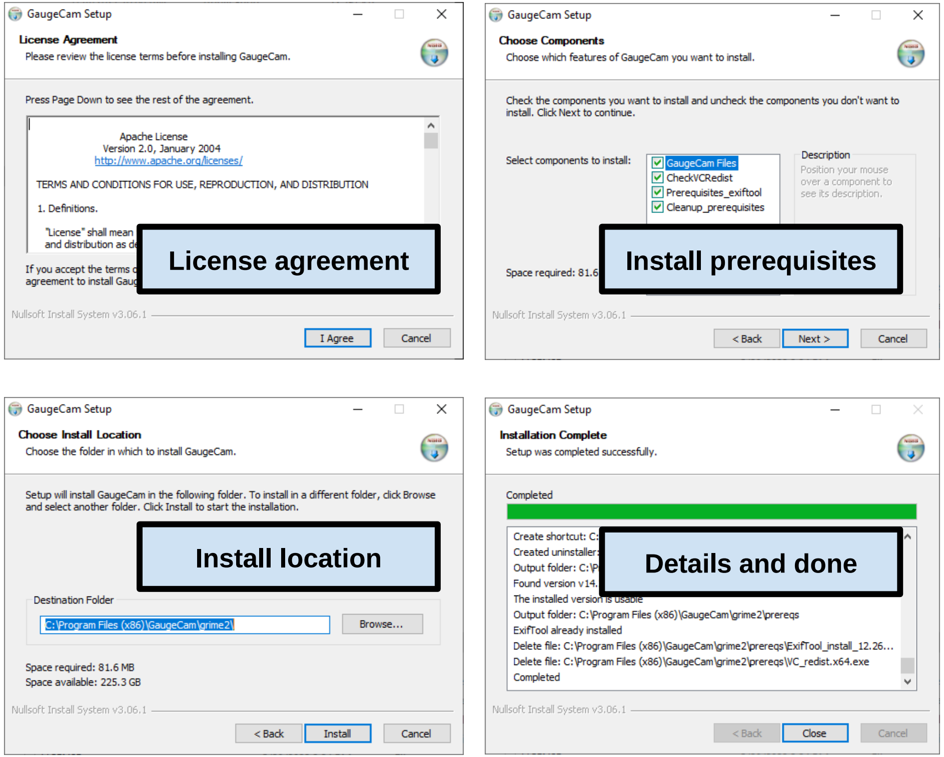
Reduce target footprint



Study information content of semi-conditioned images

GRIME2 Software Package

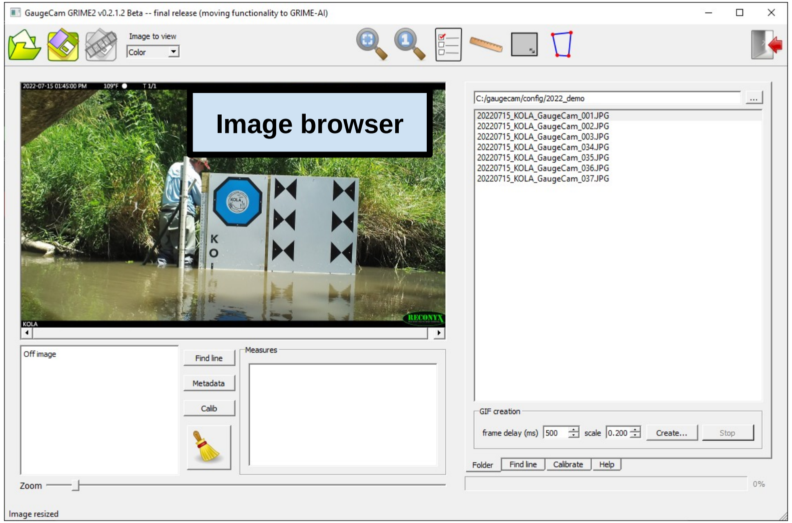
Solutions—Installer (Windows)

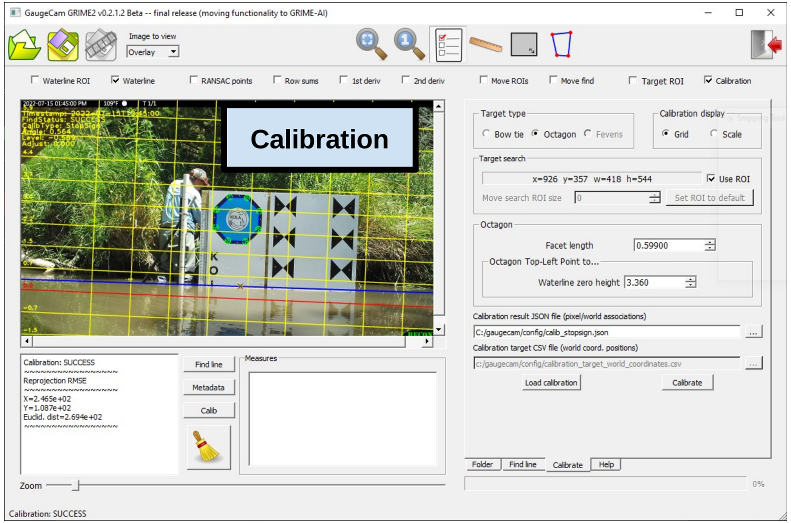


- Installer and source code available for download from GitHub
- Commercial friendly, free, open-source Apache 2.0 license
- Installs all prerequisites automatically
- One-click uninstall
- Installs both the Graphical User Interface (GUI) and Command Line Interface (CLI) versions of the program
- Installs demo images and calibration for everything necessary to test the program after installation

GRIME2 Software Package

Solutions—Graphical User Interface 1 of 2





Standard tools image tools

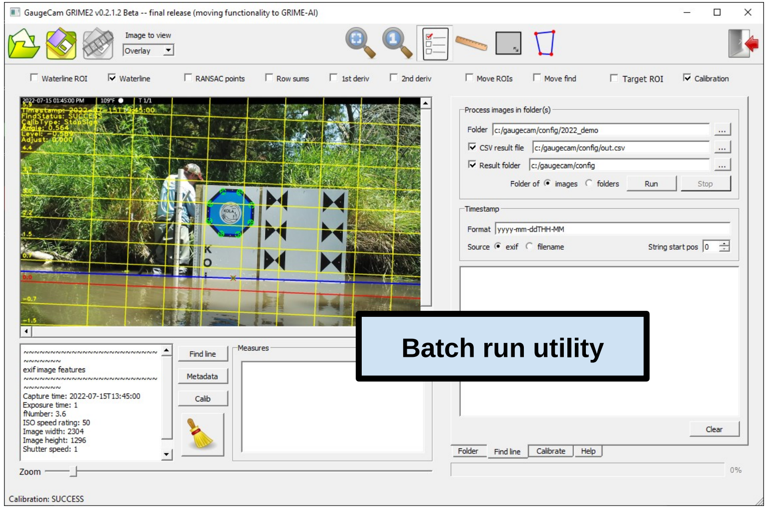
- Zoom (1:1, to fit, continuous)
- Pan
- Click through image folder
- Color, grayscale, overlay modes
- Load and save images
- Create animation

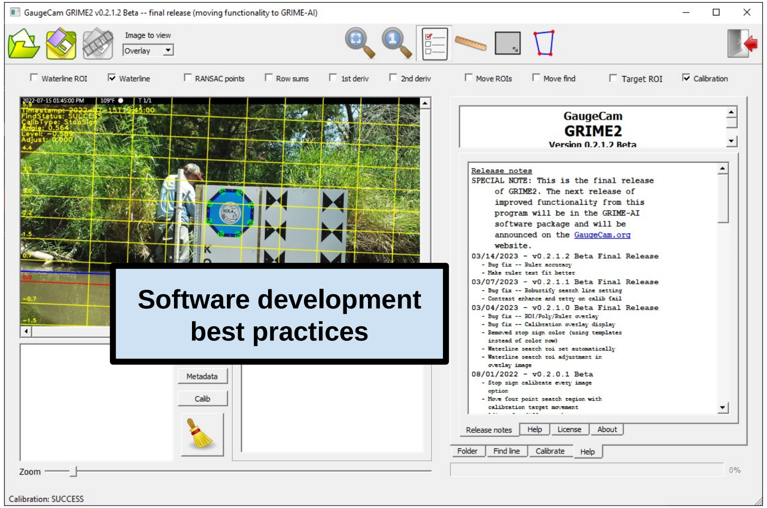
Improved calibration

- One-click calibration
- Calibration overlay (grid and scale)
- Read image metadata
- Load/save calibration files
- Show calibration error
- Set search regions of interest

GRIME2 Software Package

Solutions—Graphical User Interface 2 of 2





Batch run mode

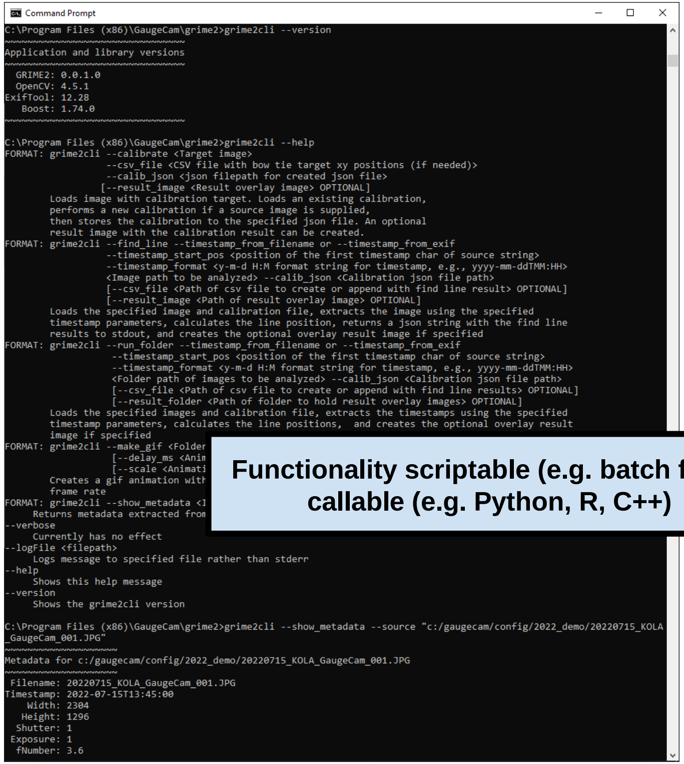
- Run folders of images
- Output results as CSV files
- Get date from filename or EXIF data
- Run single or nested image folders
- Watch results as the happen in GUI
- Output overlay result images for use in publications or animations

Miscellaneous

- Standard versioning
- Release notes specify changes
- Documentation written with Doxygen
- Common libraries with open-source licenses (OpenCV, Qt, Boost, etc.)
- Developed on Linux platform—runs in Linux and Windows

GRIME2 Software Package

Solutions—Command Line Interface



Functionality scriptable (e.g. batch files), callable (e.g. Python, R, C++)

- Command Line Interface (CLI) version of the program is part of the standard installation
- Batch mode is useful to run many images and folders of images
- All functionality of the GUI available from the command line
  - Version
  - Help
  - Show image metadata
  - Calibrate image
  - Run folders of images
    - Output CSV file
    - Output overlay result images
  - Create animations

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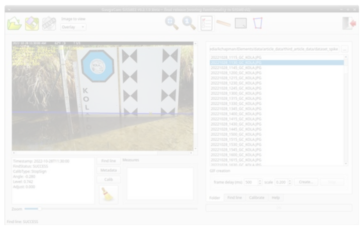

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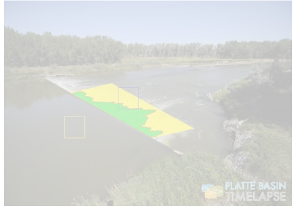
Reduce target footprint

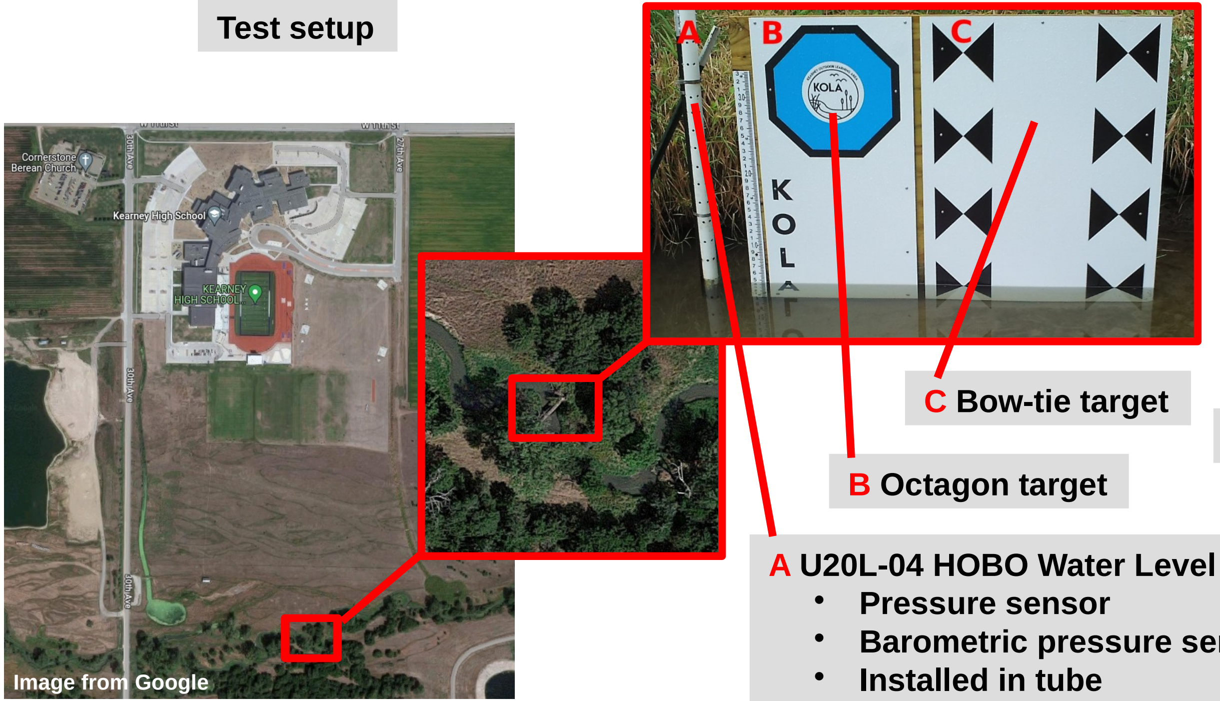


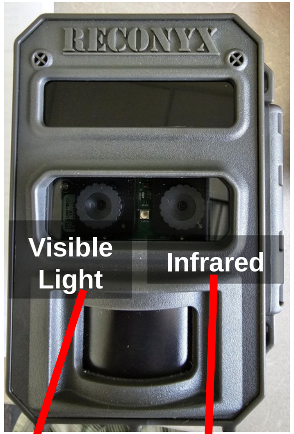
Study information content of semi-conditioned images

GRIME2 Target Improvement—Experiment Installation

Kearney Outdoor Learning Area (KOLA)

Test setup





Daytime

Nighttime

C Bow-tie target

B Octagon target

A U20L-04 HOBO Water Level Data Logger

- Pressure sensor
- Barometric pressure sensor
- Installed in tube
- Single scalar value per reading

GRIME2 Target Improvement—Ground truth issues

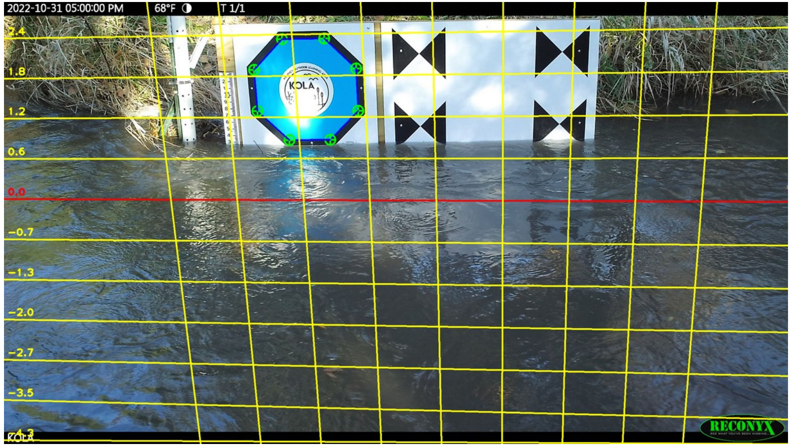
Typical causes for HOBO sensor error

- The effect of debris build-up on t-posts and PVC pipe (this can affect the height of the water right at the pipe).
- The sensor was covered in sediment after the large event, which could have increased pore pressure and therefore perceived water level.
- The sensor was sitting on top of sediment that was then washed away during the high flow event.
- Sensor movement within the pipe
- Barometric sensor under water.

Use HOBO sensor scalar readings as imperfect "ground truth"

HOBO sensor and barometric pressure sensor housed in tube

GRIME2 Target Improvement—Octagon target



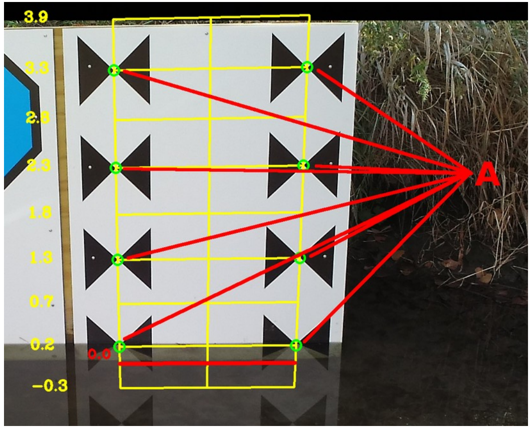
Octagon Image Processor

- Full perspective transform calculated in most images
- No special camera movement adjustment required

Bow-tie Image Processor

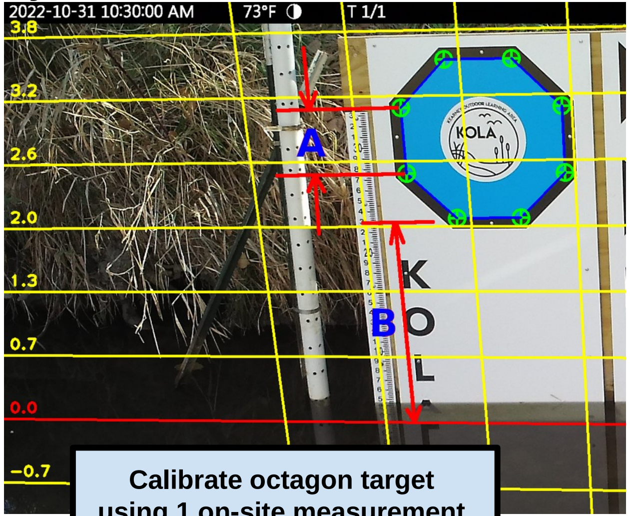
- Water frequently covers some of the bow-ties
- Calibration can occur only when all bow-ties are visible
- Move detection is required to adjust for possible camera movement
- Move adjustment accommodates translation (not a full perspective transform)

GRIME2 Target Improvement—Octagon Target



Octagon target inputs

- A Facet length
- B Distance from bottom-left to zero level
- Only one measurement at installation site



Calibrate octagon target using 1 on-site measurement, instead of bow-tie target's 16

Bow-tie target inputs

- Requires measurement of world coordinate positions (A) for all eight bow-ties for which a transom is needed to measure the positions accurately
- Values entered into a separate, specifically formatted file to be read by the calibration program

GRIME2 Target Improvement—Error comparisons

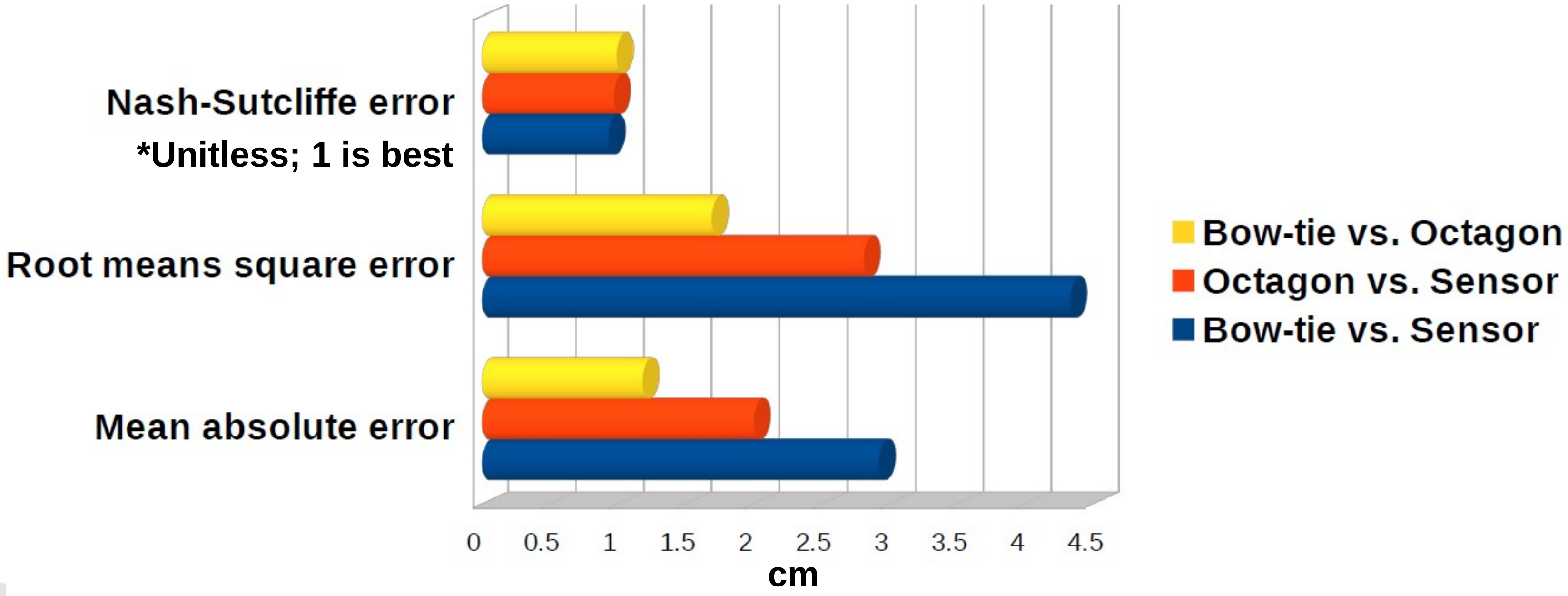
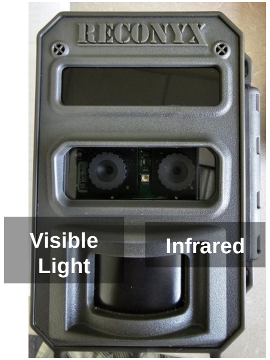


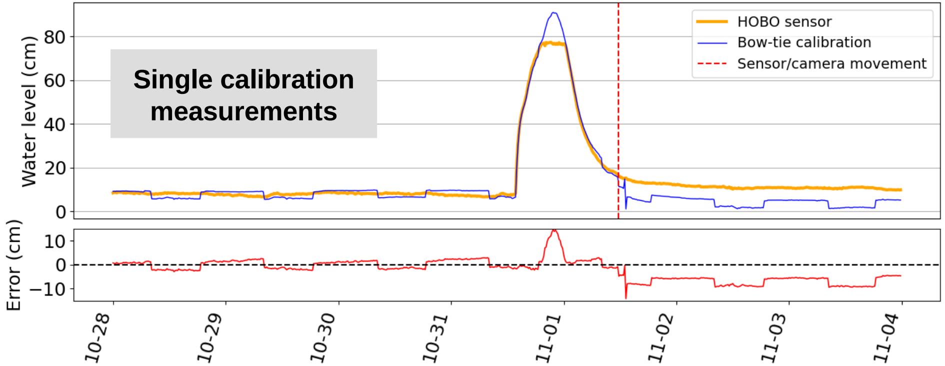
Image-based measurement corresponds well with traditional sensing

GRIME2 Target Improvement—Bow-tie results

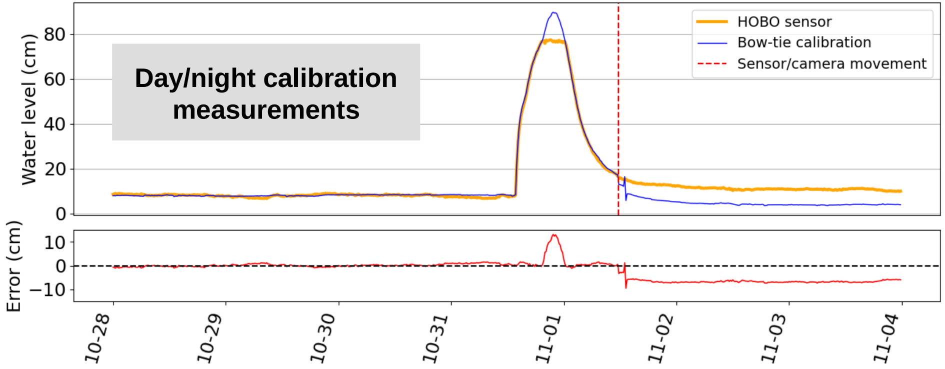


Aberrations

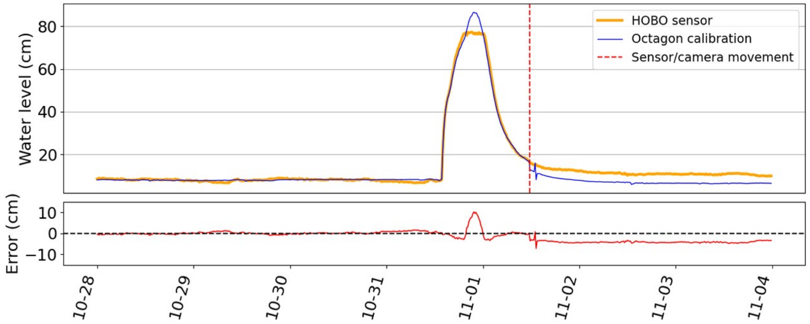
1. Single Halloween night spike
   - Manual evaluation shows this really happened
2. Plateau in Hobo data
3. Square wave in bow-tie curve
4. Rise in Hobo data toward end of spike
5. Rise/fall in image data toward end of spike

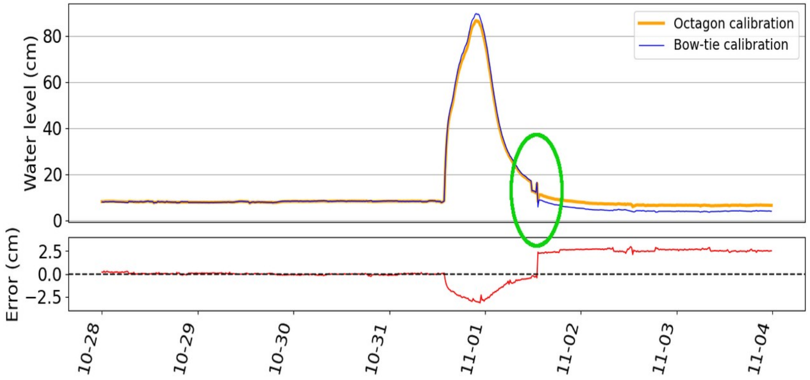


Calibration required for each sensor



GRIME2 Target Improvement—Octagon results





Observations

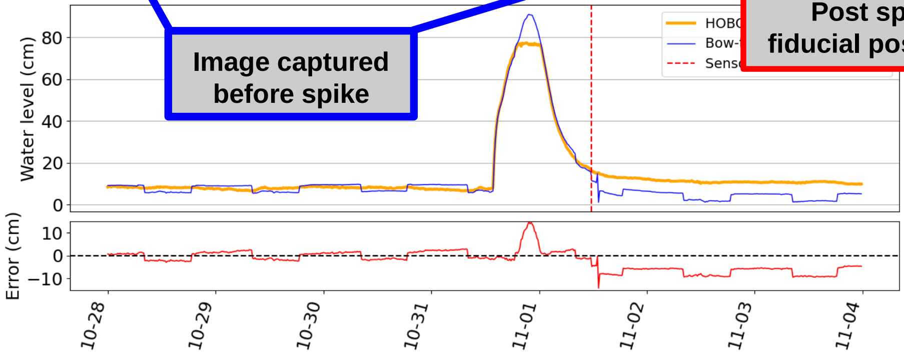
- **Octagon calibrates each time for the sensor that captured the image**
- **Spikes in green ellipse present in image but not sensor measurements**

GRIME2 Target Improvement—Camera move event

What caused the sensor/image difference after the spike? The camera moved

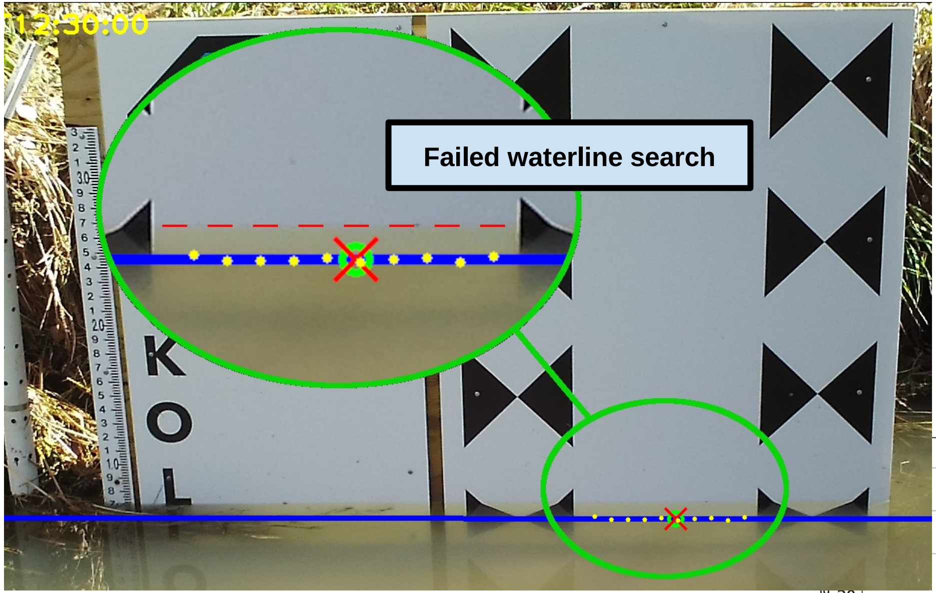
Post spike fiducial positions

Image captured before spike

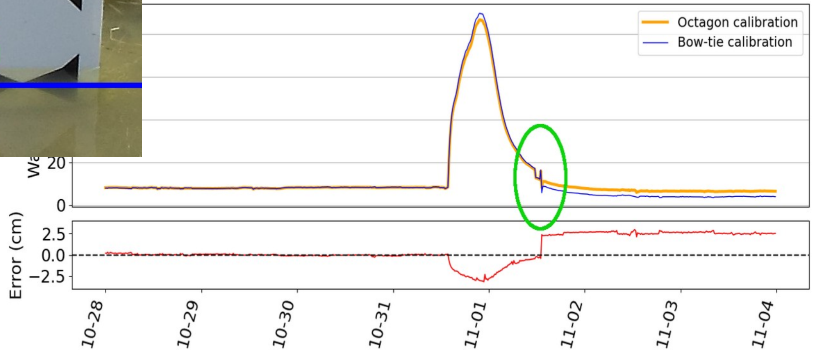


Dashed red vertical line in graph corresponds with camera maintenance and end of the spike event

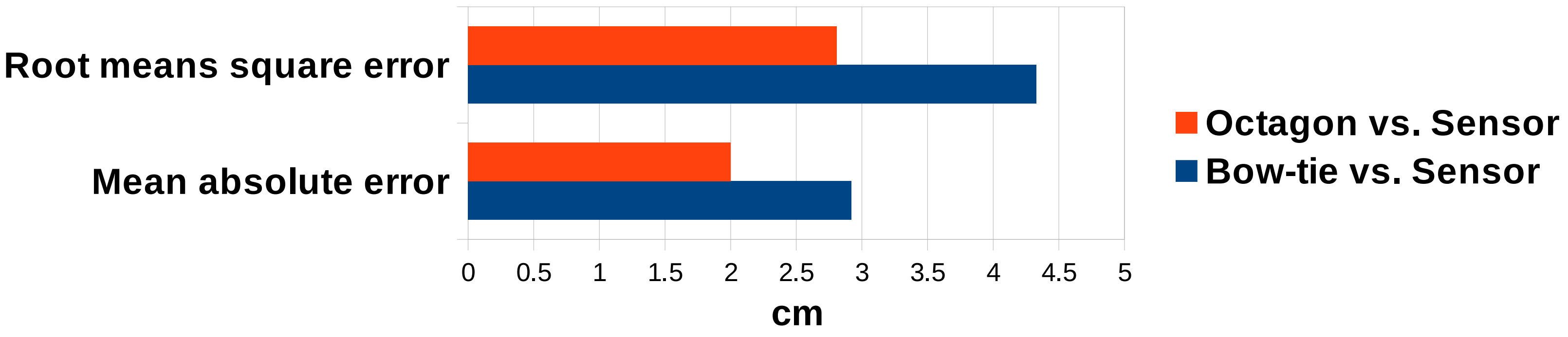
GRIME2 Target Improvement—Line find fail

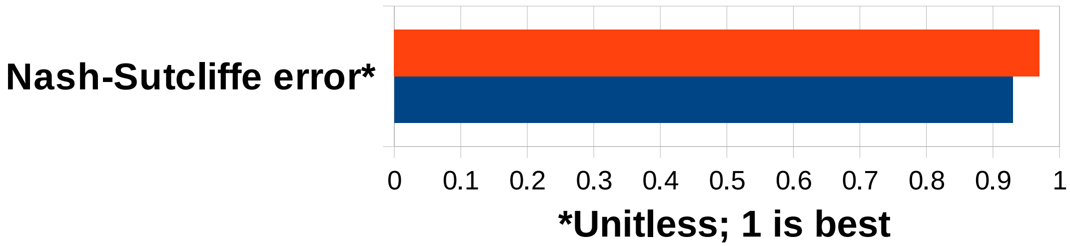


Manual image evaluation showed
the waterline search algorithm failed in these instances



GRIME2 Target Improvement—Error comparisons





Octagon target more consistent with HOBO sensor measurements

GRIME2 Algorithm Sensitivities

- **Target must be orthogonal to the surface of the water**
  - **Generalization to non-orthogonal targets involves complicated measurements: target & camera's orientation**
- **Target must be stationary across measurements**
  - **Re-calibration and/or camera move detection does not fit target movement error**
- **Target must not be obscured by biofouling**
  - **Use better target materials**
- **Opportunity for future research**
  - **Use a stereoscopic, LIDAR, or projected point grid 3D camera**
  - **Design a 3D calibration target from which orientation can be derived**

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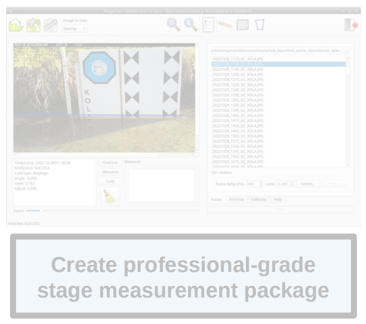
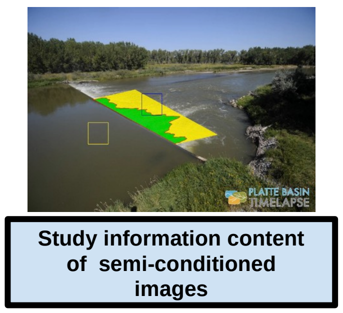
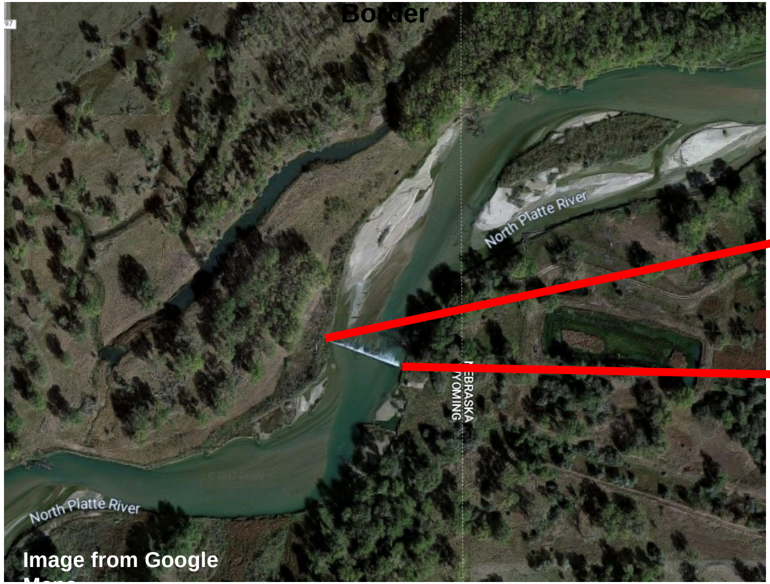


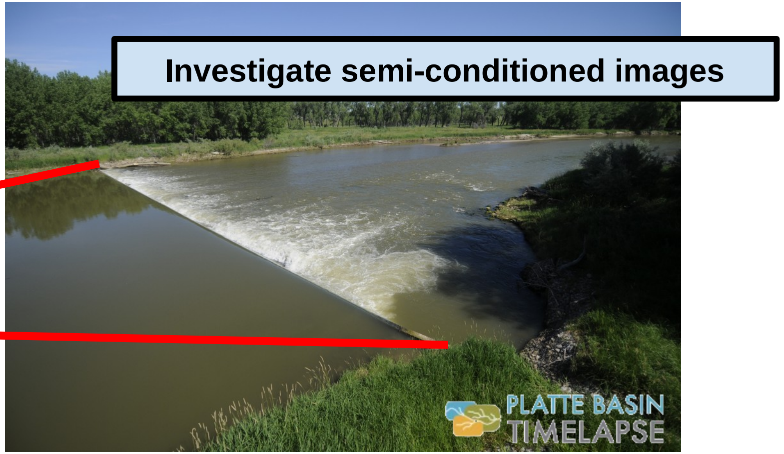


Stage and discharge from documentary time-lapse imagery

North Platte River Stateline Weir on the Nebraska/Wyoming Border

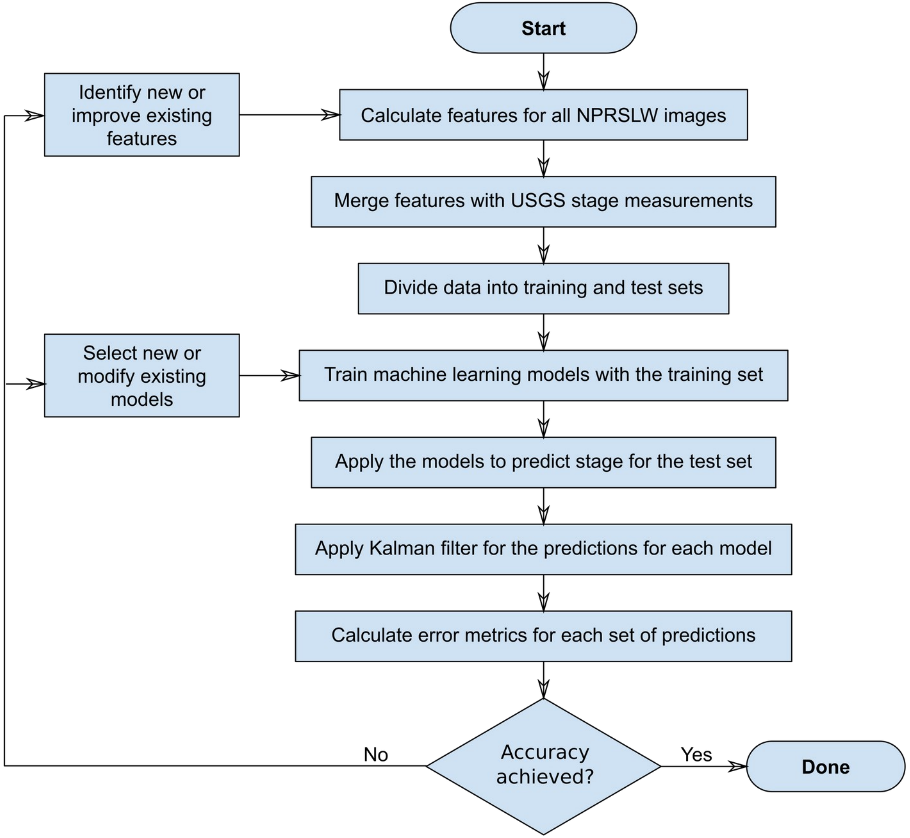


STUDY QUESTION: Is there enough information in the images to predict stage and discharge to fill year-long data gaps using USGS stage and discharge data as ground truth (no manual image annotation)?

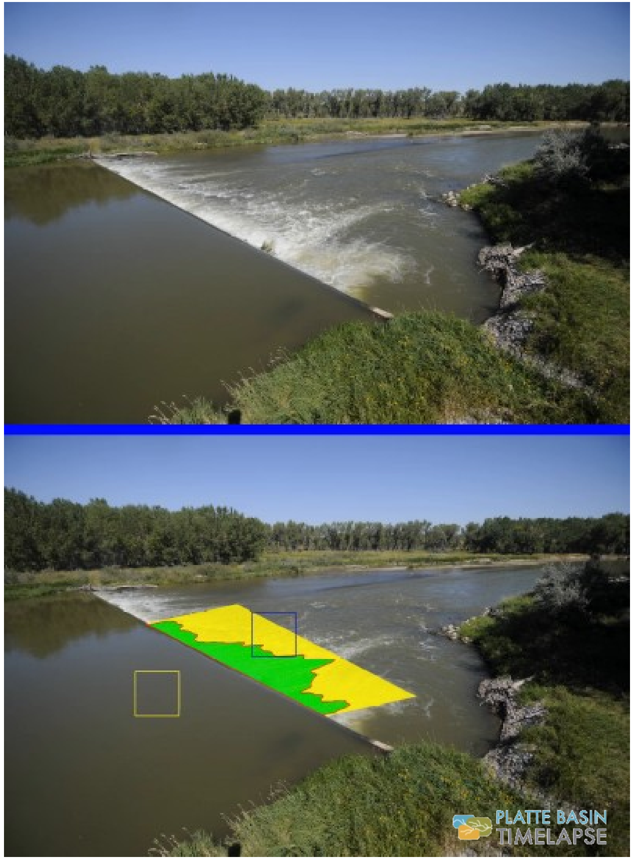


- Nothing special placed in the image for calibration
- Weir serves as a fiducial
  - Time-series image alignment
  - Upstream/downstream demarcation
- USGS stage sensor and discharge data at same site

Stage and discharge from documentary time-lapse imagery



Stage and discharge from documentary time-lapse imagery



Graphical overlay of features calculation regions

Example features regions

- Whitewater region (green)
- Above weir region (yellow square)
- Below weir region (blue square)
- Whole image

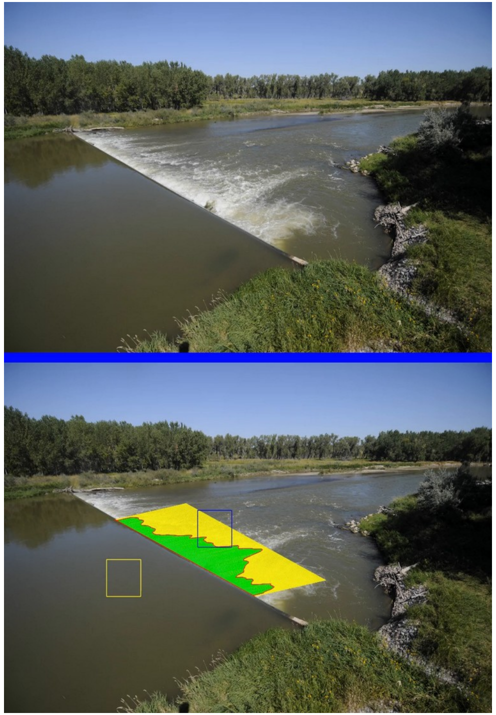
Example features

- Area of whitewater
- Tortuosity of whitewater outer boundary
- Length of whitewater outer boundary
- HSV mean and sigma of all regions
- Shannon entropy mean and sigma of all regions
- Edge magnitude mean and sigma of all regions

Gap estimations

- Artificial data gaps for 2015, 2016, and 2017 filled with estimations from classifiers created with the designed features

Stage and discharge from documentary time-lapse imagery



Graphical overlay of features calculation regions

Example features regions

- Whitewater region (green)
- Above weir region (yellow square)
- Below weir region (blue square)
- Whole image

Example features

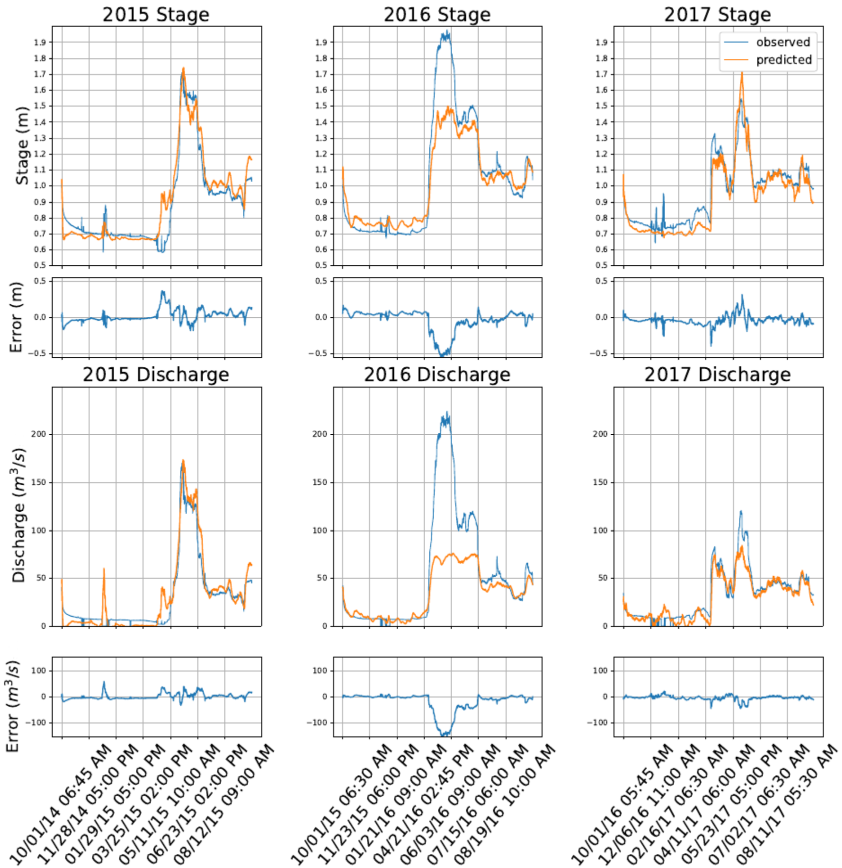
- Area of whitewater
- Tortuosity of whitewater outer boundary
- Length of whitewater outer boundary
- HSV mean and sigma of all regions
- Shannon entropy mean and sigma of all regions
- Edge magnitude mean and sigma of all regions

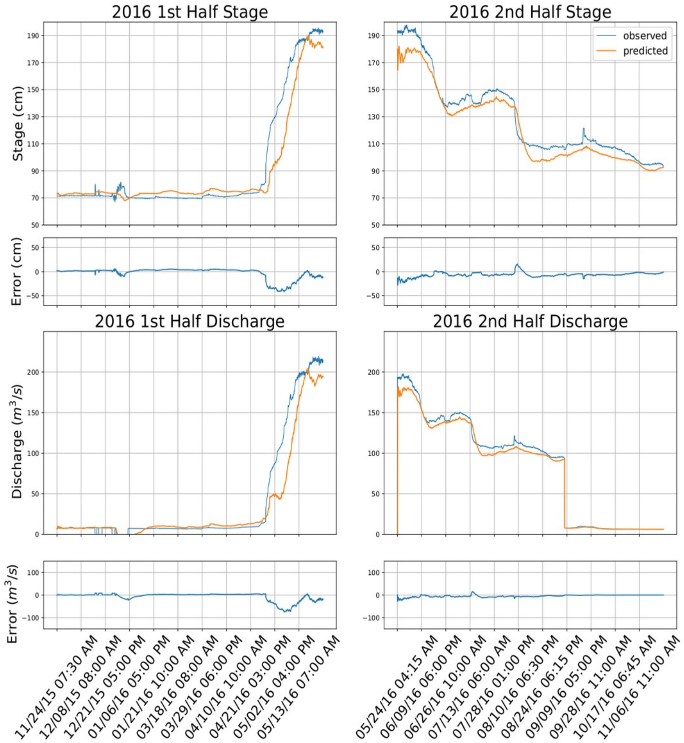
Gap estimations

- Artificial data gaps for 2015, 2016, and 2017 filled with estimations from classifiers created with the designed features

PLATTE BASIN TIMELAPSE

Stage and discharge from documentary time-lapse imagery





Agenda

1) Background
2) Studies
    A) GRIME2 software package
    B) GRIME2 target improvement
    C) Stage and discharge from documentary time-lapse imagery
3) Conclusions and future research
4) Acknowledgments
5) Questions

1) Conclusions

Goals achieved

- Provide an easy-to-use, free, open-source, software tool for academia, industry, and government to measure stage.
- Improve the GRIME2 methodologies to move its capability up and to the right on the Image Conditioning Levels Curve.
- Determine whether ground-based imagery from a single site holds enough information to accurately predict stage and discharged well enough to fill gaps based on scalar measurements before and after the gaps.

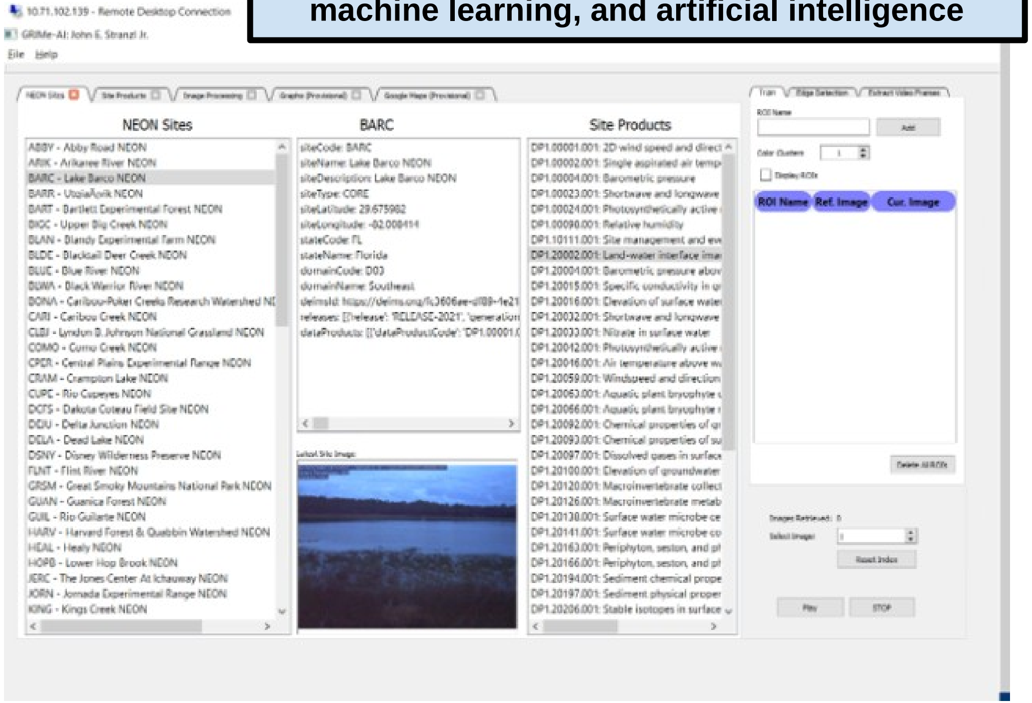
- Establish new relationships and continued old relationships based on our research with other institutions for use and development of the tools:

  - North Carolina State University
  - Texas A&M—Corpus Christi
  - Instituto Tecnologio de Estudios Superiores de Monterrey
  - University of Kansas
  - Idaho Power
  - United States Geological Survey

1) Future research

- **Move further to the right on the image conditioning levels curve**
  - **Improvement of GRIME2 tools to measure with targets not required to be orthogonal to the water measurement surface**
  - **Development of a GRIME-AI tool to perform data access and fusion, image triage, segmentation, and fully and semi-automated annotation, machine learning, and artificial intelligence**

GRIME-AI is in process at the GRIME Lab
Data access, fusion, image triage, annotation, machine learning, and artificial intelligence



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1) Acknowledgements

Committee
- Troy E. Gilmore
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- Andrew Harms

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- Frank Evans
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- Seminar class instructors
- Short course instructors

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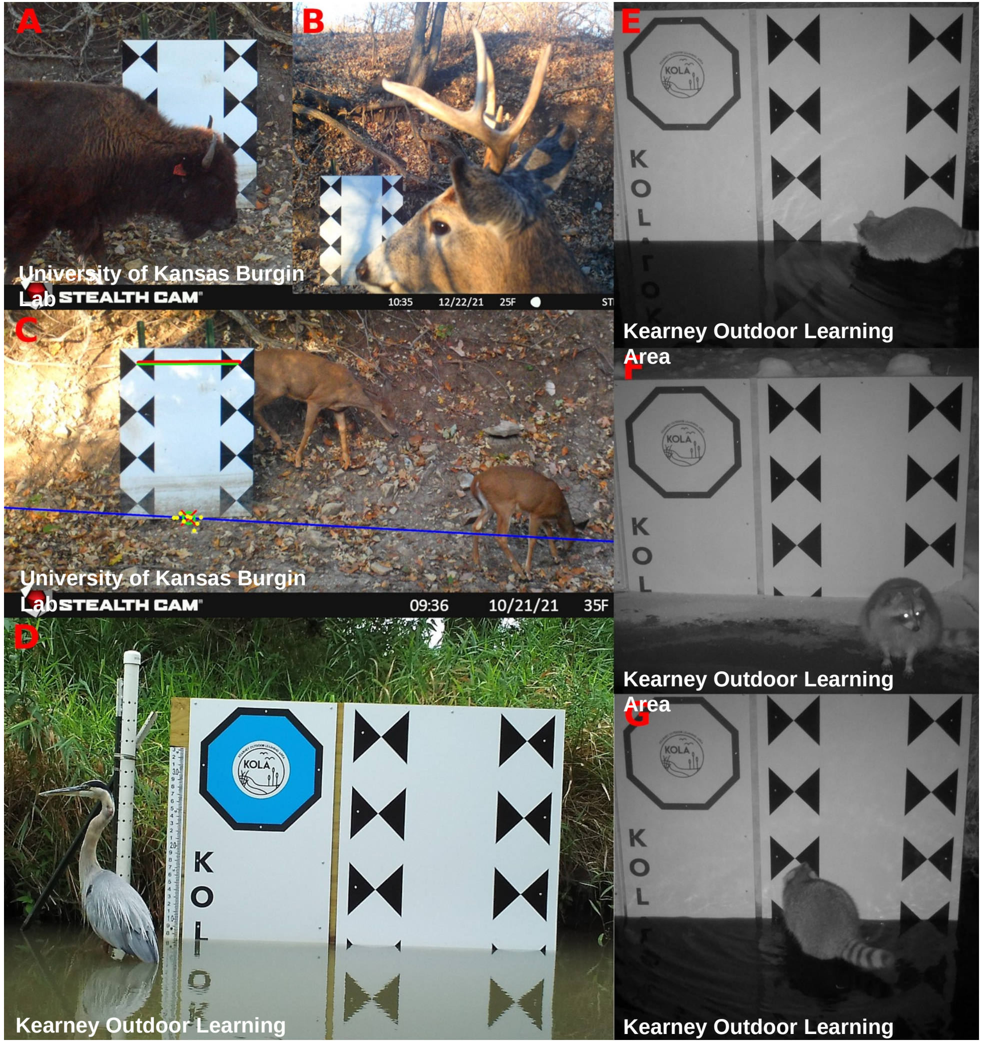
- Mario De la Fuente

Family
- Wife—Lorena
- Kids—Christian and Kelly
- Parents—Milo and Sarah
- Mexican family—Lauro, Conchita, Lauro, Jr. Jorge, Lynn, and Rigoberto

Agenda

Questions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Kearney Outdoor Learning
Kearney Outdoor Learning

THE END

Significance

Premises

- Images offer a more complete record of stream conditions than gauges that record
  only a scalar value for each measurement

- There is no good way to measure or predict stage and discharge in images with
- the same precision as water level sensors without high levels of scene conditioning

- High levels of scene conditioning increase installation, maintenance, and usage complexity and cost

- Less image conditioning is better if measurement precision and ease-of-use can be maintained

GRIME2 Target Comparison

Image vs. sensor measurement error with filtering

Measure	Ref	MAE[D.2]	MSE[D.3]	RMSE[D.4]	NRMSE[D.5]	RSR[D.6]	NSE[D.8]	PBIAS[D.7]
Median filter								
Bowtie	Sensor	2.92	18.69	4.32	0.30	0.27	0.93	13.99
Octagon	Sensor	2.00	7.87	2.81	0.19	0.18	0.97	9.44
Outlier removal with running average filter								
Bowtie	Sensor	2.91	18.65	4.32	0.30	0.27	0.93	14.06
Octagon	Sensor	2.00	7.86	2.80	0.19	0.18	0.97	9.50
Kalman filter								
Bowtie	Sensor	2.92	18.77	4.33	0.30	0.27	0.93	13.99
Octagon	Sensor	2.11	9.93	3.15	0.22	0.20	0.96	9.10

MAE – Mean absolute error
MAE – Mean square error
RMSE – Root mean square error
NRMSE – Normalized root mean square error
RSR – RMSE-observations standard deviation ratio
NSE – Nash-Sutcliffe error
PBIAS – Prediction bias

Stage and discharge from documentary time-lapse imagery

Comparisons to other Stage and Discharge Gap-Filling Studies

Table 5. Comparison of inputs, data time resolution and error metrics for studies that predicted stream stage and discharge.

Study	Time interval	Feature count	Inputs	RMSE range	NSE range	RSR range	PBIAS range
Stage				**m**			**m**
Chapman et al. (2023)[1]	Hour	42	On-site[2]	0.06 to 0.23	0.63 to 0.90	0.11 to 0.37	-4.88 to 8.83
Chen et al. (2020) [20]	Day	4	Off-site[3]	1.12 to 1.71	0.65 to 0.71	N/A	N/A
Seo et al. (2018) [26]	Day	1	On-site[4]	0.00 to 0.04	0.97 to 1.00	N/A	N/A
Gong et al. (2016) [21]	Month	4	On/Off-site[5]	0.59 to 1.59	0.06 to 0.69	N/A	N/A
Yoon et al. (2011) [22]	Six hours	3	On/Off-site[6]	0.17 to 0.19	0.53 to 0.63	N/A	N/A
Discharge				**m^3/sec**			**m^3/sec**
Chapman et al. (2023)[1]	Hour	42	On-site[1]	7.85 to 45.21	0.45 to 0.90	0.10 to 0.37	-24.15 to 37.38
Chen et al. (2020) [20]	Day	4	Off-site[3]	13.54 to 19.56	0.54 to 0.83	N/A	N/A
Tfwala et al. (2013) [16]	Day	3	Off-site[7]	124.71 to 150.36	0.97 to 0.98	N/A	N/A
Jain et al. (2012) [27]	Day	1	On-site[8]	N/A	0.77 to 1.00	N/A	N/A

[1] This study (One year gap predictions only)
[2] Data: Images, Training set: 5,000 before and 5,000 after gap, Test set: All gap year images – 5643 to 7377 images
[3] Data: Pumping rates, recharge rates, discharge from two other stations, Training set: Data from 1986-2008, Test set: Data from 2009-2010
[4] Data: Lagging stage from same site, Training set: Stage measurements from 2009-2014, Test set: 2015-2016
[5] Data: Precipitation, temperature, lagging stage from same site, nearby lake level, Training set: Data from 1998-2007, Test set: Data from 2008-2009
[6] Data: Precipitation, tide level, lagging stage from same site, Training sets: 06/04-08/04, 05/05-11/05, Test sets: 11/04-12/04, 05/20-11/06
[7] Data: Discharge from three other sites, Training set: 1997-2009 (70%), Test set: Data from 1997-2009 (10%)
[8] Data: Lagging discharge from same site, Training set: 2004-2005, Test set: 2006

GRIME2 Target Improvement

Image vs. sensor measurement error

Measure	Ref	MAE[D.2]	MSE[D.3]	RMSE[D.4]	NRMSE[D.5]	RSR[D.6]	NSE[D.8]	PBIAS[D.7]
Bowtie	Sensor	2.92	18.77	4.33	0.30	0.27	0.93	13.99
Octagon	Sensor	2.00	7.92	2.81	0.19	0.18	0.97	9.44
Bowtie	Octagon	1.18	2.87	1.69	0.13	0.10	0.99	5.03

MAE – Mean absolute error
MAE – Mean square error
RMSE – Root mean square error
NRMSE – Normalized root mean square error
RSR – RMSE-observations standard deviation ratio
NSE – Nash-Sutcliffe error
PBIAS – Prediction bias

Stage and discharge from documentary time-lapse imagery

Tools and Processes

- North Platte River Stateline Weir Data
  - USGS stage and discharge data were downloaded from their website
  - The Platte River Timelapse Project provided images of the weir on a hard disk drive

- Software
  - A C++ program was written to create a comma separated values of the image file paths merged with the stage
    and discharge measurements closest in time to the image capture times
  - A C++ program was written to calculate features from the images using the OpenCV imaging library
  - A C++ program was written to create the random 30% training set and 70% test set of all the data to identify new features
  - The Weka machine learning program was used to create Random Forest Regression (RFR), Support Vector Regression (SVR), and Multilayer Perceptron (MLP) classifiers to create year-long stage and discharge measurement gaps
  - An Excel spreadsheet was created to calculate the error metrics for each of the classifiers
  - by year compared to ground truth as represented by the USGS stage sensor and discharge data
  - Python programs were written to create bar and line graphs to show the results

Stage and discharge from documentary time-lapse imagery

Comparisons to other Stage and Discharge Gap-Filling Studies