Estimating River Surface Velocity Using Optical Remote Sensing Techniques

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Abstract: River discharge is an important parameter to quantify for flood monitoring and water quality, particularly in the state of Kansas where the two major rivers originate from neighboring states. Typically, stream discharge is measured via stream gauges. The stream gauge itself measures the height of a river's surface and discharge is estimated using a rating curve. The United States Geological Survey (USGS) maintains many stream gauges, but the gauges are very sparse, especially in western Kansas. As a result, large segments of rivers in Kansas are not well monitored. In this study, I present the results of a new remote sensing method for estimating stream velocity. I use optical imagery to calculate a ratio algorithm, which is then converted into surface velocities. The remotely sensed data allows for stream velocity monitoring of river sections where there are no stream gauges and/or no or little *in situ* measurements are collected. To test the methodology, small sections of various rivers (~1 km in river length) with stream gauges are picked as test sites, including on the Kansas River (Lecompton), the Republican River (Clay Center), and the Arkansas River (Syracuse).

We use the near infrared band of Landsat 7 ETM and Landsat 8 OLI imagery, to calculate water velocity from 2010-2015. Various ratio algorithms were tested and compared with the coincident USGS stream gauge data. Calculating surface velocities is stage one of this project and the next stage will be to use these surface velocities as one of the main parameters in an entropy-based method to compute the cross-sectional area, and subsequently the discharge, of the various river sections. With the methodology working, the end goal of this project is to use this technique of stream discharge estimation of Kansan rivers as a prototype for rivers in glaciated regions of the Himalayas where stream gauges are scarce or nonexistent.

Study Sites:

- This research was conducted on the Kansas River, along the section where the Lecompton, KS USGS stream gauge is located. The study covered ~2Km of the river, all of which was located upstream of the stream gauge.

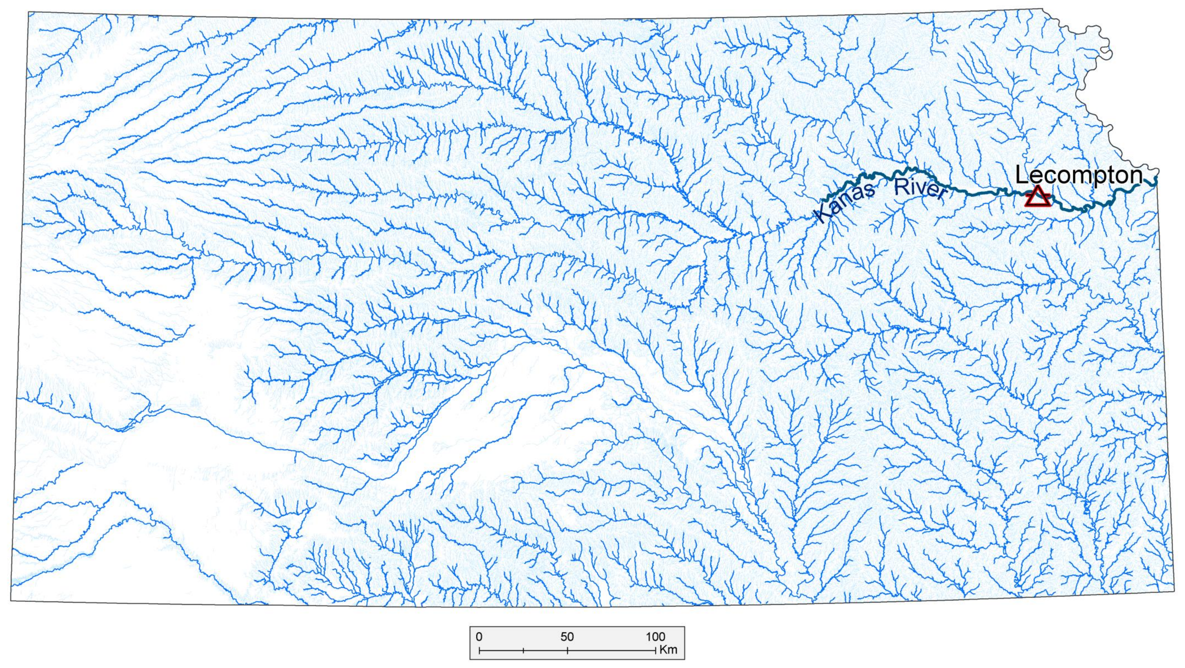

Figure 1: Map of Kansas stream with the three test sites highlighted. Water file from DASC (2013)

Methodology:

- We've adapted remote sensing methodology developed by Tarpanelli et al. (2013) that calculates stream discharge using near-infrared (NIR) imagery. In our study, we use imagery with a higher spatial resolution, and experiment with various approaches for selecting the NIR values.

Data:

- This study uses Landsat 4/5 TM, Landsat 7 ETM+ & and Landsat 8 OLI imagery over the period January 2010-November 2015.

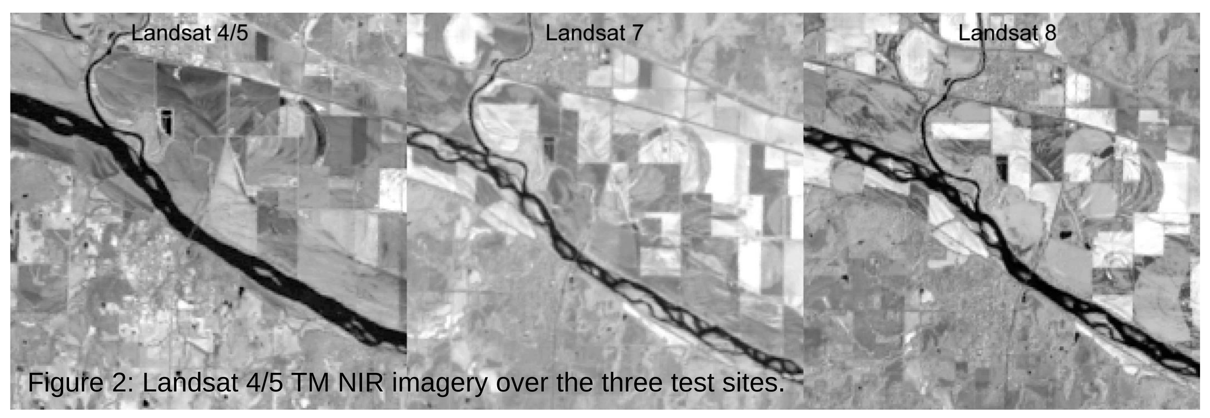

Figure 2: Landsat 4/5 TM NIR imagery over the three test sites.

Optimization of pixel selection:

- The ratio algorithm requires NIR values representing land (C) and water (M).

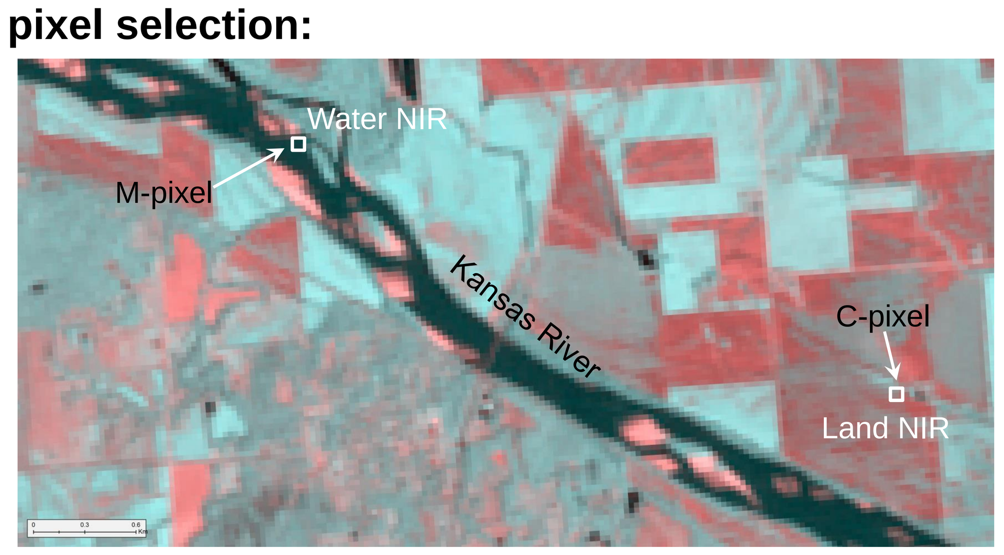

Figure 3: Landsat 4/5 TM NIR imagery over the three test sites.

- To choose the "best" NIR values for land and water, two methods were tested

Correlation Coefficient:

$$= \frac{\sum(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum(x_i-\overline{x})^2\sum(y_i-\overline{y})^2}}$$

- Pearson's R was calculated for every C/M ratio combination with USGS *in situ* stream mean velocities
- Highest correlation = C/M combination

Normalized Difference Water Index (NDWI):

$$NDWI = \frac{Green\ Band - NIR\ Band}{Green\ Band + NIR\ Band}$$

- NDWI was calculated for every image
- Green Band = Landsat .52-.60μm band
- Highest value = water pixel (M)
- Lowest Value = land pixel (C)

Ratio Algorithm:

$$\frac{C}{M_{t_{n+1}}} = \frac{C}{M_{t_{n+1}}} + K_{t_{n+1}}\left[\frac{C}{M_{t_{n+1}}} - \frac{C}{M_{t_n}}\right]$$

$$K_{t_{n+1}} = \frac{K_{t_n}}{K_{t_n} + e^{-\left(\frac{t_{n+1}-t_n}{T}\right)}}$$

M - NIR Water Value; C - NIR Land Value; $\frac{C}{M_{t_n}}$ - Filtered ratio

K_{t_n} - Gain; T - Time length; t_n - Time of image

Results:

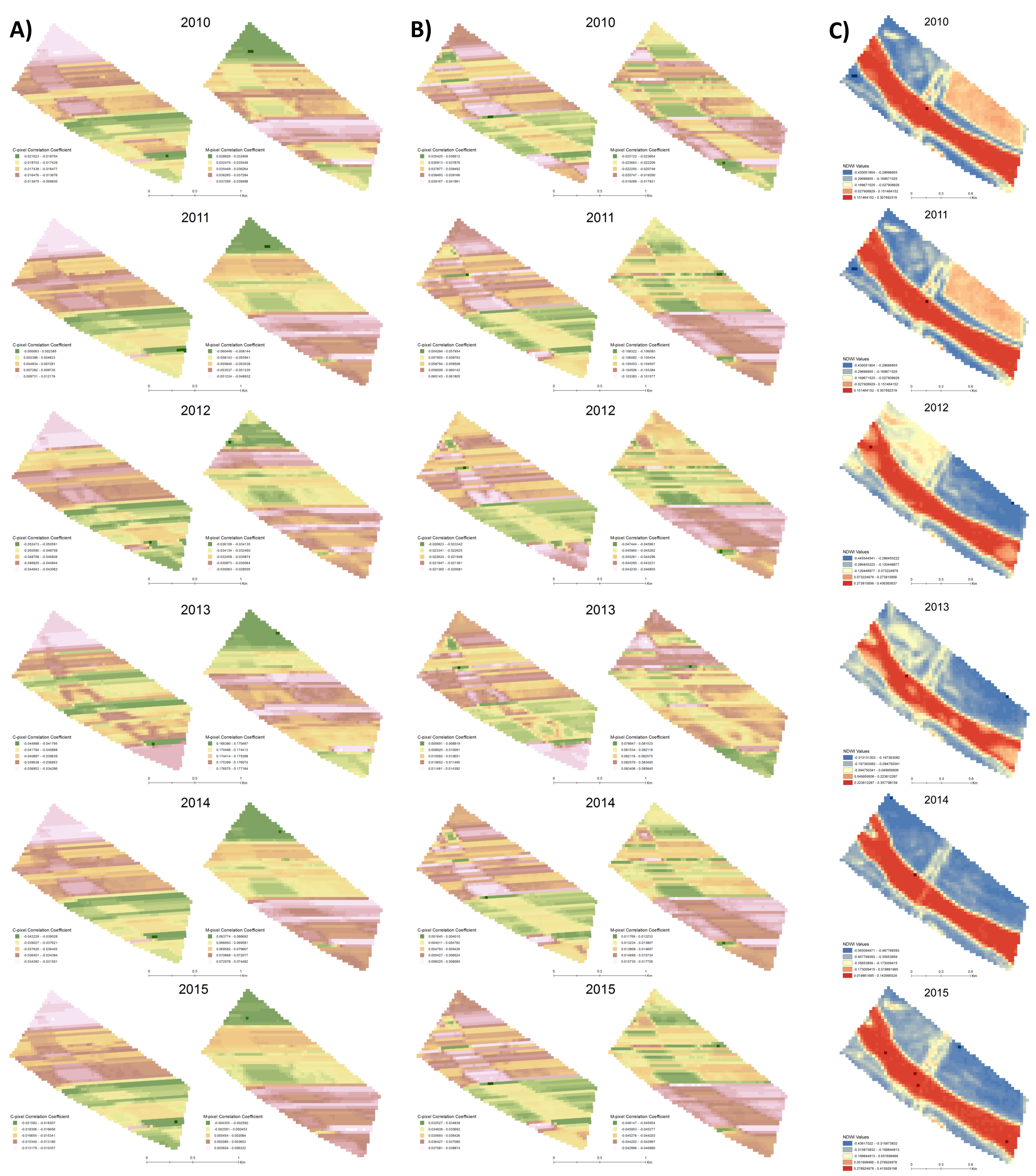

Figure 4: A) and B) are maps of highest correlation coefficient for Discharge (A) and Velocity (B). C-pixels are on the left and M-pixels are on the right. C) are the NDWI results.

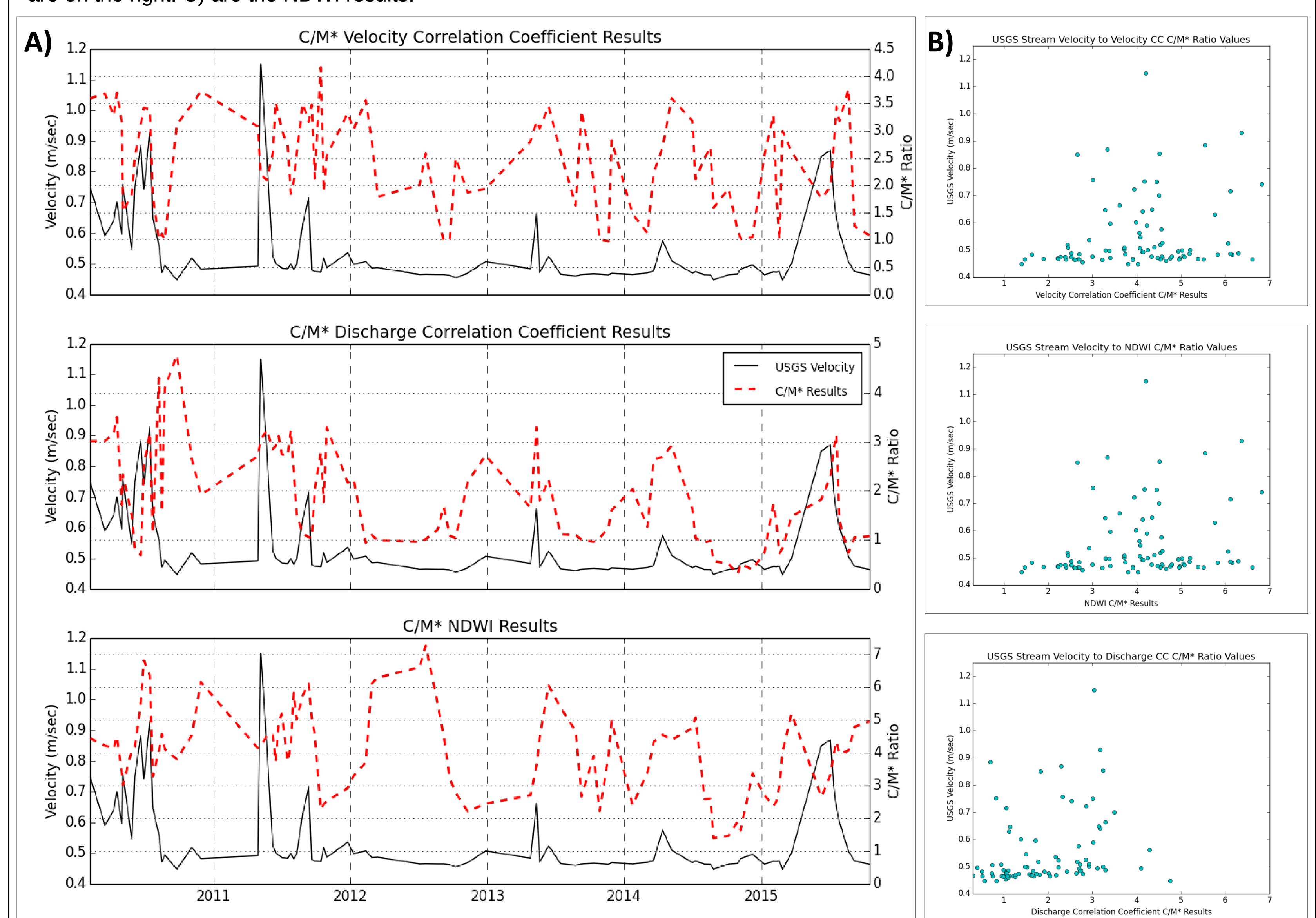

Figure 5: A) Plots show C/M* results plotted with USGS *in situ* stream velocities. B) Scatter plots of C/M* results plotted against *in situ* USGS velocities.

Next Step:

Estimate Stream Discharge with Entropy Theory

- The next step of the project is estimating river cross sectional area Moranarco et. al., (2013) using Entropy Theory.
- Entropy theory is a probability distribution function that estimates what the probability of the river's bathymetry is based on the surface velocity.
- With the cross-sectional area, the discharge of the river may be estimated.

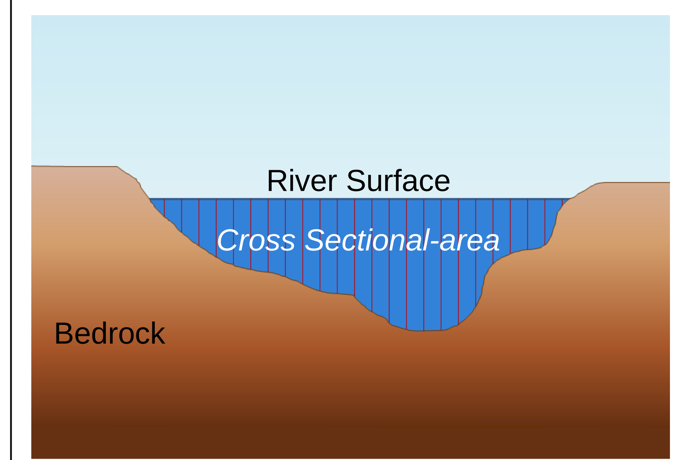

Figure 6: River cross-sectional area

Entropy Theory

$$H(X) = -\sum_j p(X_j)\ln p(X_j)$$

$H(X)$ - Shannon (1948) entropy function

X_j - Finite number of states

$p(X_j)$ - Probability

Stream Discharge

$$Q = Av$$

Q - Discharge

v - Velocity

A - Cross-sectional area

Discussion/Conclusion:

- The spikes in the C/M* plots in Figure 5 are mostly due to interpolated values for the velocity file used in calculating the correlation coefficient.
- These extreme C/M* values occur when a change in river flow have occurred (e.g. a flooding event), but the interpolation did not pick up on it.
- New methods of interpolation (such as zero-padding) will be investigated further before beginning the second phase of this project.
- This type of study has never been conducted on rivers like the Kansas River. The sand bars that evolve constantly affect the NIR values in the imagery, which ultimately affect the C/M* values.

Gangotri Glacier:

- The methodology used to estimate stream discharge on the Kansan Rivers will also be used on Bhagirathi River, located in the North-central Himalayas in India at the terminus of Gangotri Glacier.
- The aim of this study will be to separate the amount of snow melt v. the amount of ice melt that is contributed to Bhagirathi River.
- Knowing the quantity of annual ice melt produced will aid in the understanding of the future state of Himalayan Glaciers.

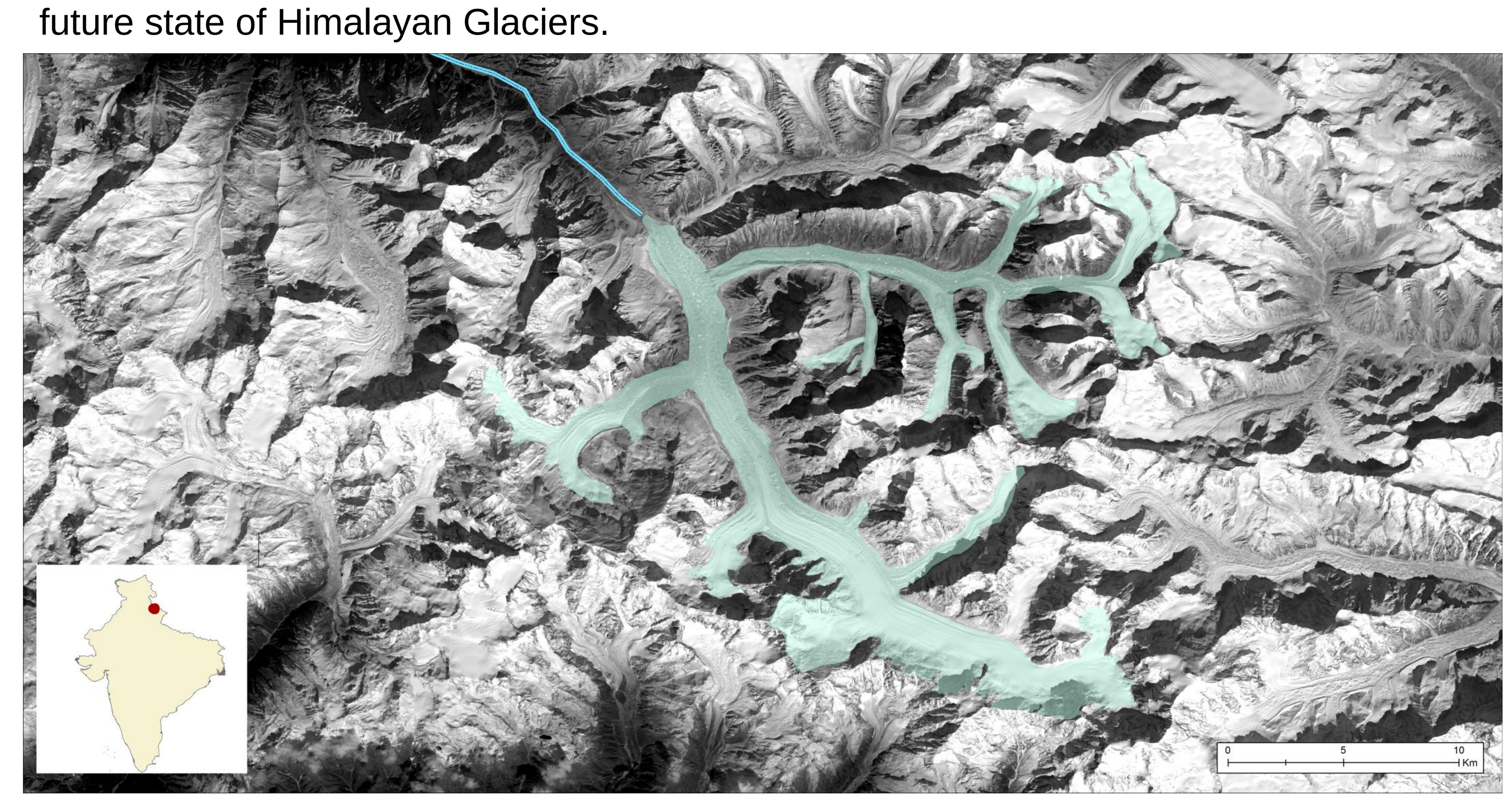

Figure 6: Map depicting Gangotri Glacier (aqua green). Bhagirathi River flows from the terminus to the Northwest.

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References:

Moramarco, Tommaso, Giovanni Corato, Florisa Melone, and Vijay P. Singh. "An entropy-based method for determining the flow depth distribution in natural channels." *Journal of Hydrology* 497 (2013): 176-188.

Tarpanelli, Angelica, Luca Brocca, Teodosio Lacava, Florisa Melone, Tommaso Moramarco, Mariapia Faruolo, Nicola Pergola, and Valerio Tramutoli. "Toward the estimation of river discharge variations using MODIS data in ungauged basins." *Remote Sensing of Environment* 136 (2013): 47-55.