Remote Sensing of River Discharge to Expand the USGS Streamgaging Network

Dave Bjerklie, John Fulton, Robert Mason, John Jones
United States Geological Survey
Charon Birkett, University of Maryland
ESSIC

AWRA National Capital Region Section
Water Resources Symposium
April 7, 2017
University of the District of Columbia

** All data herein is considered provisional and subject to change **
The Need

The current USGS streamgaging network in the United States, particularly in Alaska, does not provide full coverage in space and time.

Given the access limitations to many rivers, methods are needed to increase the spatial and temporal density of the gaging network including:

• satellite platforms
• ConFiRM (Calibration of River Measurements)
  - CalVal of top width, slope, velocity, and discharge using ground-based and rapid deployment of equipment including:
    - Fixed- and drone-based velocity radars and LSPIV cameras
    - Ungaged basins with little or no historical discharge records
The Goal

Develop and test methodologies to estimate river discharge from remotely-sensed (RS) observations with the goal of establishing discharge records where historical streamflow information is lacking.

The Objectives

Develop an approach (presented here) that couples the USGS dynamic surface-water extent product with satellite altimetry to estimate discharge from satellite observed water-surface height, slope, width, and calibrated with minimal ground-based measurements.

Establish reach scale remote sensing gaging stations in un-gaged and remote rivers that:

• Are more stable in time than cross-section based stations, reducing the frequency of supplemental ground-based measurements in un-gaged and remote basins
• Produce time series of estimates of discharge, depth, and velocity in river reaches going forward in time and enabling the reconstruction of past time series from archived RS observations
Overview – Remote Sensing
Observational Data – Dynamic Mapping of Rivers

• Observations of Dynamic Stage and Water Surface Slope

• Along-channel variation of Width and Meander Length

• Channel morphology and Meander Pattern
Detect whether surface water is present in any clear, shadow free Landsat pixel.

Provisional Version 1 data available by request.

Currently assessing inclusion of Sentinel sensor data for Version 2.

Comprehensive system in place for product evaluation/application (see poster).

POC: John W. Jones, jwjones@usgs.gov
Dynamic Surface Water Extent (DSWE)

Reach Analysis – Yukon River near Eagle, Alaska.

Landsat image analysis of width variation and meander length.
Time Series of Water Area - Tanana and Chena Rivers near Fairbanks, Alaska from DSWE

Temporal Resolution – 7 days depending on Clouds and overlapping orbital paths
Jason 2 Satellite tracks – Tanana and Chena Rivers near Fairbanks Alaska

Jason 2 overpass locations (16)

Jason 2 orbital path

10-day temporal resolution

Slope Time series for the Tanana River Jason 2 site 16

Jason-2 data presentation from Charon Birkett, UMD
Mapping River Water Surface Slope – Tanana River

Gradient of the Tanana River Cycle 112 July 2011

Tanana River Average Summer Reach Slopes from Jason-2/OSTM
Mapping the River Channel Water Surface Slope as it relates to channel pattern – Tanana River
A practical necessity using different satellite platforms – non-coincident observations

There are many more height observations from Jason 2 than width observations from Landsat due to cloud cover.

A relation is developed between width and height. Height is used to estimate width.

The upcoming NASA SWOT mission (launch 2021) will provide coincident observations of width, stage, and slope.
Supplemental information –

Assumptions from river hydraulic data – HYDRoSWOT data base

Data available for calibration –

Modeling and national hydrography data – Calibration to Mean flow

Limited discharge measurements from ground or aerial platforms – Calibration to individual measurements
HYDROSWOT DataBase - USGS Measurement Data

Assembled discharge measurements from USGS streamgages at unobstructed cross-sections using ADCP measurements, high water mark and gage height of zero flow.

https://www.sciencebase.gov/catalog/item/57435ae5e4b07e28b660af55

Table 1 – HYDROSWOT - Hydraulic and channel geometry database.

<table>
<thead>
<tr>
<th>Table Name</th>
<th>Number of Records</th>
<th>Number of Fields</th>
<th>Minimum Date</th>
<th>Maximum Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWM 1</td>
<td>13,905</td>
<td>14</td>
<td>10/6/1932</td>
<td>11/25/2014</td>
</tr>
<tr>
<td>ADCP 3 and Boat Measurements</td>
<td>223,764</td>
<td>56</td>
<td>10/7/1940</td>
<td>11/25/2014</td>
</tr>
</tbody>
</table>

1 = High water mark; 2 = Gage-height of zero flow; 3 = acoustic Doppler current profiler
HYDROSWOT DataBase - USGS Measurement Data

Selected fields of interest for each streamgage measurement:

- Drainage Area at the gage
- Latitude and Longitude of the gage
- Elevation of the gage
- Discharge
- Flow width
- Maximum and mean depth of flow
- Maximum and mean velocity of flow

Anticipate adding channel slope at each gage in the near future.
Example – Based on HYDROSWOT data, the ratio of maximum to mean depth can provide a general guide to channel cross-section shape.

Based on 30,000 flow measurements in rivers across the US, the ratio of mean to max depth is approximately 1.5, which indicates a general parabolic shape.
USGS remotely sensed, ground-based stage and velocity radars for Cal/Val – ConFiRM

USGS Streamgage: Rio Grande at Embudo, New Mexico, USA.

Comparison of streamflow derived from standard stage-discharge rating and real-time continuous-wave radars for the USGS streamgage 08279500 Rio Grande at Embudo, NM.
How is discharge computed and what variables change to generate real-time discharge:

The Probability Concept parameter, \( \phi \) or \( \frac{u_{avg}}{u_{max}} \) established on 4/30/14 remained unchanged and used to compute subsequent Qs; however, \( u_{max} \) and area, which are measured in real-time differ:

**9/27/14 at 0300:**

\[
Q = \phi u_{max} A
\]

\[
Q = 0.606 \times 2.87 \text{ ft/s} \times 157 \text{ ft}^2
\]

\[
Q = 273 \text{ cfs vs 273 cfs}
\]

**6/14/15 at 2000:**

\[
Q = \phi u_{max} A
\]

\[
Q = 0.606 \times 8.60 \text{ ft/s} \times 420 \text{ ft}^2
\]

\[
Q = 2,188 \text{ cfs vs 2,220 cfs}
\]
USGS Ground-based Radar – Wide with high sediment load – note high scatter due to sample duration or wind drift.

USGS Streamgage: Tanana at Nenana, Alaska USA.

Comparison of streamflow derived from standard stage-discharge rating and real-time continuous-wave radars for the USGS streamgage 15515500 Tanana River at Nenana, AK.
Discharge Algorithm Development

Testing Manning Equation (MAN) with a logarithmic modifier for change in resistance with depth, and Prandtl-von Karman (PVK) Equation with base flow resistance estimated from channel characteristics and various options for calibration.

\[
\text{MAN: } Q = \frac{W \ast \left( (h-B) \ast \left( 1 - \left( \frac{1}{1+r} \right) \right) \right)^{1.67} \ast S^{0.5}}{n}
\]

\[
\text{PVK: } Q = 2.5 \ast W \ast Y \ast (g \ast Y \ast S)^{0.5} \ast (ln \left( \frac{Y}{y_0} \right) - 1)
\]
Discharge Algorithm Variable Definitions

where:  
Q = the river discharge, (m$^3$/s)  
W = the width of flow, (m)  
h = the water surface stage (height) above a common datum, (m)  
S = the water surface slope between observations of stage  
n = the Manning roughness (resistance) coefficient  
B = the stage of zero flow, (m)  
r = the assumed channel shape coefficient.  

\[ Y = (h - B) \times (1 - \frac{1}{1+r}), \text{ (m)} \]  
\[ y_0 = \text{roughness height, (m)} \]  
g = gravitational constant, 9.81 m/s$^2$
## Remotely-sensed Hydraulic Features Used to Compute Discharge

<table>
<thead>
<tr>
<th>Observed Feature</th>
<th>Variable</th>
<th>State</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Surface Area</td>
<td>Reach averaged width</td>
<td>Dynamic</td>
<td>Landsat DSWE</td>
</tr>
<tr>
<td>Water Surface Height</td>
<td>Change in depth</td>
<td>Dynamic</td>
<td>Jason2 Satellite altimetry</td>
</tr>
<tr>
<td>Water Surface Height</td>
<td>Water surface slope</td>
<td>Dynamic</td>
<td>Jason 2 Satellite altimetry</td>
</tr>
<tr>
<td>Channel Pattern</td>
<td>Index to roughness</td>
<td>Static</td>
<td>Landsat DSWE</td>
</tr>
</tbody>
</table>
Case Study for Yukon River at Eagle and Stevens Village – Stage and Slope from Jason-2 Altimeter

Jason-2 flight lines

Stevens Village

Eagle

Jason-2 flight line used for stage and slope

USGS gage

USGS gage

Jason-2 flight lines used for stage and slope
Case Study of Yukon River at Eagle and Stevens Village – Reach Averaged Width and Channel Meander Pattern

Landsat image with channel water surface area delineated Using the Dynamic Surface Water Extent (DSWE).
Case Study for Yukon River at Stevens Village

Jason-2 flight lines

USGS gage

Jason-2 flight line used for calculations

Jason stage vs. USGS stage

Linear (USGS stage)

Water surface slope, m/m

Case Study for Yukon River at Eagle

Jason-2 flight lines

Jason-2 flight line used for calculations

![Graph showing Jason 2 stage vs. USGS stage](image)

- Jason 2 stage, m above datum
- USGS stage, m above datum
- Linear (USGS stage)

![Graph showing water surface slope vs. date](image)

- Water surface slope, m/m
- Dates from 2/22/2008 to 5/10/2016

\[ V_b = 1.37 \times (\lambda_c S)^{0.32} \]

- \( V_b \) - bankfull mean velocity
- \( Y_b \) - bankfull mean depth

\[ n_b = \frac{Y_b^{0.67} S^{0.5}}{V_b} \]

- \( n_b \) - bankfull Manning flow resistance

\[ n = n_b \times (1 + \log \left( \frac{H-B}{h-B} \right)) \]

- \( \lambda_c \) - Resistance length
- \( S \) - water surface slope

\[ n = n_b \times \left( 1 + \log \left( \frac{H-B}{h-B} \right) \right) \]

**Calibrated** – Using three discharge measurements assumed available from limited ground-based measurements collected during the eight year period of record.

\[ n = n_b \times \left( \frac{H-B}{h-B} \right)^x \]

- \( x \) - variable exponent
- \( H \) - bankfull stage
- \( B \) - bottom stage
- \( h \) - stage at flow

Varying \( n_b \) and \( x \) to match the three measurements.
Eagle Calibrated

![Graph showing comparison of discharge data between different methods]

<table>
<thead>
<tr>
<th>Eagle Alternate</th>
<th>Remote</th>
<th>Remote</th>
<th>Error MAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>USGS</td>
<td>MAN</td>
<td>PKV</td>
</tr>
<tr>
<td>Mean</td>
<td>4273.79</td>
<td>4364.25</td>
<td>4741.80</td>
</tr>
<tr>
<td>Stdev</td>
<td>1427.48</td>
<td>1457.91</td>
<td>1065.78</td>
</tr>
<tr>
<td>Coef. Var.</td>
<td>0.33</td>
<td>0.33</td>
<td>0.22</td>
</tr>
<tr>
<td>Max</td>
<td>11952.1</td>
<td>5</td>
<td>7919.32</td>
</tr>
<tr>
<td>Min</td>
<td>1316.01</td>
<td>1507.01</td>
<td>2365.23</td>
</tr>
<tr>
<td>NSE</td>
<td>0.83</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>NRMSE</td>
<td>0.06</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>
Stevens Village Calibrated

- Remote Estimated Discharge, m$^3$/s vs. USGS Discharge, m$^3$/s
- Data points for MAN Q, PVK Q, and Linear (USGS Q)

### Comparison Statistics

<table>
<thead>
<tr>
<th>Stevens Alternate</th>
<th>Remote</th>
<th>Remote</th>
<th>Error MAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>USGS</td>
<td>MAN</td>
<td>PKV</td>
</tr>
<tr>
<td>Mean</td>
<td>6975.33</td>
<td>7047.00</td>
<td>6910.69</td>
</tr>
<tr>
<td>Stdev</td>
<td>3036.42</td>
<td>3202.90</td>
<td>2217.06</td>
</tr>
<tr>
<td>Coef. Var.</td>
<td>0.44</td>
<td>0.45</td>
<td>0.32</td>
</tr>
<tr>
<td>Max</td>
<td>19370.9</td>
<td>0</td>
<td>22534.75</td>
</tr>
<tr>
<td>Min</td>
<td>2221.09</td>
<td>2663.53</td>
<td>3518.61</td>
</tr>
<tr>
<td>NSE</td>
<td>0.98</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>NRMSE</td>
<td>0.02</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

**Stevens Village Calibrated**
General Strategy for Using Satellite Information to Estimate Discharge and Develop RS gaging stations

To provide control on accuracy, a limited field calibration program will be needed.

The calibration can be accomplished:

• Using rapidly deployed and temporary gaging station installations used for a short period of time
• Modeling and hydrologic data to derive mean estimates of discharge
• Using aerial platforms to measure discharge and other hydraulic variables on a limited periodic basis – stay tuned for the next presentation by Jon Nelson and others
For Fun - Contrast with USGS Remote Measurements at Eagle 1911 - 1914
This white strip was graduated in black paint at intervals of a quarter of a foot and the even feet were marked with numbers large enough to be read by a telescope from the hotel piazza at Eagle, about half a mile distant.

The only feasible method for making open-channel discharge measurements of the Yukon is by floats. About 2 miles above Eagle a stretch of channel was selected which is straight for about 1,000 feet and through which its cross section was believed to be practically uniform.
In 1912 three measurements were made, two with ice and driftwood when it was coming down the river in sufficient quantities to serve as floats and one by means of bottle floats. For the bottle floats beer bottles were weighted with sand and were marked with flags stuck in the necks. White flags were found to be best adapted to be seen at a distance over the water surface. These floats were dropped by a boatman in a rowboat at intervals of about 75 feet across the stream above the upper range line.

The instruments used were a transit and a stop watch. The passage of ice cakes was timed and their location was determined by triangulation. As an ice cake crossed the upper range one man followed it with the transit telescope, the other went down to the lower range and when the float crossed signaled the transitman and noted the time.
Stage-Discharge Rating Curves for Yukon River at Eagle

1914

2017

USGS science for a changing world