Application of Satellite Based Altimetry to Estimation of Surface Water Level and Discharge

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Dave Bjerklie (1), Charon Birkett (2)

Yuanjie Li, Michelle Hofton, Ralph Dubayah (3)

Martina Ricko (4)

(1) Water Science Center, US Geological Survey, Connecticut, USA, Contact - dmbjerkl@usgs.gov

(2) Earth System Science Interdisciplinary Center, University of Maryland College Park, USA

Departments of Geography (3) and AOSC (4), University of Maryland College Park, USA

1. Introduction

Satellite altimetry has the ability to map and monitor variations in surface water height for large inland water bodies. A clear advantage is the provision of data where traditional gauges are lacking or where there is restricted access to ground-based measurements. Several NASA funded programs are exploring the performance of the NASA, CNES and ESA lidar and radar instruments over the largest lakes, river channels and wetlands within the USA and Canada. Validation exercises reveal level variation accuracies on the order of a few cm to tens of cm, and there are clear limitations and advantages to both techniques. Derived altimetric heights can also be combined with other satellite-based measurements to gain estimates of river discharge i.e., a process that has no reliance on ground-based gauge data. Here we utilize the ICESat/GLAS (lidar, V531 GLA14 and GLA06 products) data set and show that by combining GLAS-derived elevations and slopes with Landsat ETM-derived channel widths over the Mississippi/Missouri basins, estimates of river depth, velocity and discharge can be made. The range of accuracy and use of such data is discussed in the context of future high resolution instruments and the potential development of a satellite-based river gauging system that can enhance existing ground-based networks.

2. Objectives

OVERALL : To have an ability to determine river discharge, globally, and with minimal ground truth input. The data should ideally be obtainable as a direct product via an automated method and provide observations between ground-based sites and across large un-gauged regions.

1) Test the application of readily obtainable remote sensing products to estimate flow conditions in rivers and whether such a system can be operational over large areas.

2) Specifically, observe and deduce the river width, height, slope, depth and velocity, to gain river discharge.

3. Methodology

Flow Estimation Methods - Generalized Flow Equations

1) General Manning: $Q = 7.1*W*Y^{1.67}*S^{0.33}$

- Q = River discharge (m^3/s)
- W = mean width for the reach (m)
- Y = Mean river depth (m)
- S = channel water surface slope (m/m) (assume constant)
- (based on Bjerklie et al., 2005a)

2) Prandtl von-Karman: $V = 2.5*(g*Y*S)^{0.5}*[\ln(Y/y_0) - 1]$

- V = mean channel velocity across river section (m/s)
- g = gravitational constant (9.8 m/s^2) (constant)
- y_0 = channel bed roughness height (m) (assume constant)
- and substituting V into Q = W*Y*V to obtain discharge, Q

• Observation of elevation and slope (from satellite altimetry), and channel width (from satellite imagery).

• Both equations assume an interchange between change in stage or elevation (dE) and water depth (dY), but require a reference depth (Yr) to bring estimates of Q into the absolute frame, ie. elevation must be referenced to a depth which is associated with a particular state of flow. In this case we assume the reference depth is associated with the narrowest remotely observed river reach width (Wr) in a derived time series of width variations,

$$Yr = 0.017*Wr^{0.53}*S^{-0.28}$$

• Equation 2) also requires an estimate of the roughness height (y_0),

$$y_0 = 0.27*S^{0.43}$$

Relations include assumptions based on channel geometry, and are based on data presented in Bjerklie et al. (2005b). The depth estimating equation is determined for river flows with widths greater than 100m. These estimates are based on conditions over a wide range of rivers are not necessarily specific to the sites of interest. Calibration data, if available can be used to improve these estimates.

4. Data Sets

CASE STUDY REGION - MISSISSIPPI/MISOURI BASINS

USGS gauging stations: Mississippi at Baton Rouge ,Mississippi at Chester Illinois, and Missouri River at Hermann Missouri. Comparative data includes :

- discharge and stage at all three stations, (typical discharge errors ± 5%)
- water surface slope from topographic map information,
- mean river velocity estimates for the Missouri at Hermann and Mississippi at Baton Rouge.

River Stage+Slope –ICESat/GLAS laser altimeter

(Footprint size advantages, cloud + saturation limitations)

1) Change in water surface Elevation as an index to change in water Depth.

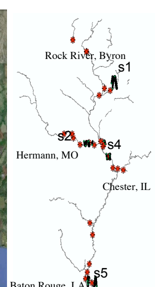
2) Water surface Slope along the reach as defined by ground track locations.

GLAS –GLAS14 version 428 data set corrected for atmospheric delays and earth tides. 2003 to 2008 observations up and downstream of gauge. Laser 2 and Laser 3 campaigns (max 3 camps. per year). Test OSTM IGDR dataset.

For River Surface Width – Landsat Thematic Mapper (TM), ETM+

(With free and easy access to image data bases)

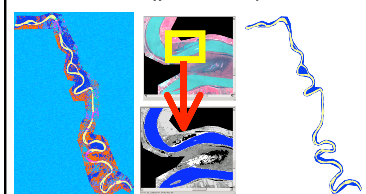
1) Average water surface width across the observed reach determined by dividing the reach area by the reach length. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) panchromatic (PAN) band with 15-meter resolution. The upper and lower boundaries for the river polygon (reach) are defined by satellite tracks. Water surface width is computed from water surface area and reach length.



5. River Surface Width

MultiSpec - Supervised and Unsupervised Classification

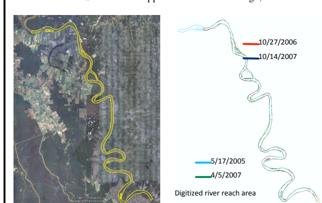
Site 5 Mississippi River at Baton Rouge, LA



Landsat TM June 29th, 2006

Manual Digitization - for Validation checks

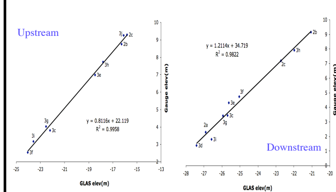
Site 5 Mississippi River at Baton Rouge, LA



6. River Elevation and Slope

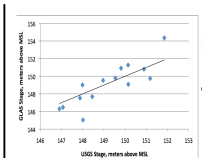
ICESat/GLAS laser altimeter data

Site 5 Mississippi River at Baton Rouge, LA



GLAS Slope=0.00003; USGS Topo Slope=0.00003

Average distance between gauge/GLAS tracks is 80/32km up/downstream. Average channel width=810m



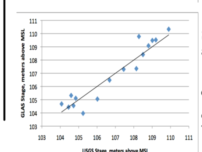
Site 2 Missouri River at Herman, MO.

R2=0.792

16km gauge/track septn.

Channel width=440m

GLAS Slope=0.00013; USGS Topo Slope=0.00013



Site 4 Mississippi River at Chester, IL.

R2=0.897

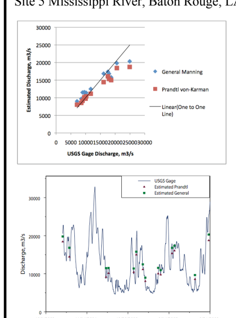
17km gauge/track septn.

Channel width=900m

GLAS Slope=0.00005; USGS Topo Slope=0.00007

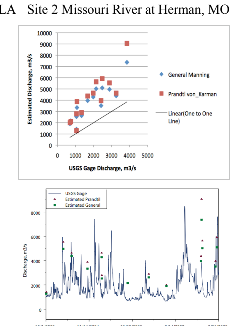
7. River Discharge

Site 5 Mississippi River, Baton Rouge, LA



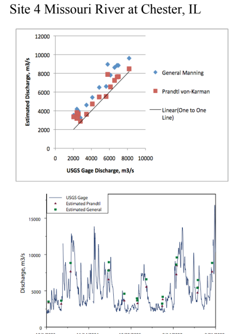
Mean (P.v.K) velocity 1.12 m/s, cf mean value reported for comparable flow conditions at the gage of 1.15 m/s (based on the US Army Corps observations of 1975-1983 at Baton Rouge). Estimated mini. depth (10 m) is comparable to the maintained channel depth 11 m (dredging). Mean discharge error for the Prandtl von-Karman equation is -5% and for Manning +7%. Both methods underestimate the largest discharges.

Site 2 Missouri River at Herman, MO



Average estimated river velocity is 1.37 m/s cf average velocity 1.08 m/s. The mean depth and width for the same discharge range is also larger for the remote measurements. Both equations overestimate discharge, especially the highest flow rate, by more than double. This error can largely be corrected by calibration of the depth to match the mean discharge.

Site 4 Missouri River at Chester, IL



The Prandtl von-Karman equation provided the best results for this gage with a mean discharge error of 20%.

8. Conclusions

- Satellite-based lidar has potential to monitor elevation and slope. Accuracy is poorer than radar altimetry but methods and corrections are still being refined.
- Despite non-synergy of elevation, slope and width estimates, the combined altimetry/imaging techniques have enabled both the dynamic and absolute variations in discharge in the Mississippi Basin - with limitations on reach, and assumptions on reference depth based within the flow equations.
- Additional laser and radar, and theoretical investigations continue in this basins and others.
- There is a forward look to emerging (CRYOSAT-2, ICESat-2) and future (SWOT) technologies to enhance observations.

7. References and Funding

Bjerklie, D.M., D.K. Moller, L. Smith and S.L. Dingman, 2005a. Estimating discharge in rivers using remotely sensed hydraulic information, J. Hydrology, V.309, pp.191-209.

Bjerklie, D.M., S.L. Dingman and C. H. Bolster, 2005b. Comparison of constitutive flow resistance equations based on the Manning and Chezy equations applied to natural rivers, Water Resources Research, V.41, W11502.

Bjerklie, D.M., C. Birkett, Y. Li, M. Hofton, R. Dubayah, Estimating river discharge using satellite-based parameters: Test case study on the Mississippi Basin, for Water Resources Research, In prep.

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