

AHGestimation: An R package for computing robust, mass preserving hydraulic geometries and rating curves

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Summary

Background

In the field of hydrology it is common to express the behavior of a river channel at a given cross section using power law equations relating top width (TW), mean depth (Y), and velocity (V) to a given discharge (Q). Collectively these equations define the “at a station hydraulic geometry” (AHG) (Leopold and Maddock 1953).

$$TW = a \cdot Q^b$$

$$Y = c \cdot Q^f$$

$$V = k \cdot Q^m$$

AHG relations apply to within-bank flows at a specific cross section and assume the channel characteristics do not significantly change with discharge. Under these assumptions, two continuity conditions determine mass conservation. When either of these is violated, the AHG’s equations will cause mass imbalances in computations.

$$Q = TW \cdot Y \cdot V$$

and therefore:

$$b + f + m = \tag{1}$$

$$a \times c \times k = \tag{2}$$

$$= 1 \tag{3}$$

Statement of need

Large scale models simulating river flow are critical for forecasting water availability, drought, and flood inundation. These models must represent the size and shape of river channels in some generalized way.

While hydraulic geometry relationships have been extensively studied, they remain unquantified for the majority of stream reaches across the country. Consequently, large-scale models frequently use incomplete approximations that impact the accuracy of streamflow estimates (Heldmyer et al. 2022; J. M. Johnson et al. 2023) and flood forecasting (Zheng et al. 2018; Maidment et al. 2014; J. M. Johnson et al. 2019; Water

Prediction 2023). At NOAA, National Water Model characteristics are based on trapezoidal geometries (e.g. (Gochis 2020)) that are in part derived from hydraulic geometry relationships and drainage area assumptions found in (Bieger et al. 2015, 2016; Blackburn-Lynch, Agouridis, and Barton 2017).

Other efforts have aimed to calculate, and synthesize river channel data at a large scale in the United States (e.g. (Enzminger, Minear, and Livneh 2023; Afshari 2019)) however each of these relied on traditional Ordinary Least Squares Regression (OLS) fitting methods *and* data preprocessing (Afshari et al. 2017). And while both efforts produced valuable data products, the software is not shared.

This open source package is designed to assist work flows that are challenged by the following characteristics of hydraulic data:

1. Data is often distributed without consistent structure
2. Data is noisy and hard to fit with traditional methods
3. Data is tabular, making the development of efficient regional and continental datasets a challenge.

Software

AHG estimates have predominately occurred on a location-by-location basis with site specific knowledge guiding the data used and the validation of the outputs. As interest in large scale model applications increases, the need to estimate these relations from disparate and often noisy datasets is increasingly important.

AHGestimation is an R package (R Core Team 2023) providing three capabilities:

1. Tools to estimate single and full system AHG relations using a robust estimation techniques that enforces flow continuity and minimizes total system error (`ahg_estimate`). This is accomplished by introducing a hybrid approach that supplements the traditional OLS approach, with a Nonlinear Least Square (NLS) regression, Evolutionary algorithm (NSGA-2; Mersmann (2020)), and ensemble modeling approach.
2. Methods to filter outliers based on time (`date_filter`), mass conservation (`qva_filter`), and statistical detection (`mad_filter`, `nls_filter`).
3. Formalize, in code, many of the concepts derived in (Dingman and Afshari 2018) that relate AHG coefficients and exponents to cross-section hydraulics and geometry. These include (`cross_section`, `compute_hydraulic_params`, `compute_n`).

The package documentation includes several examples on the theory, design, and application of this tool set.

The first stable version of AHGestimation was made available in 2019 and was applied to an aggregated dataset of USGS manual field measurements. Since then, it has been actively developed to better understand and quantify these fundamental relationships in the face of noisy, large, and disparate data sources. Applications of the software have been used to (1) demonstrate how improved flood forecasts could be delivered from the NOAA/NWS National Water Model (J. M. Johnson et al. 2022) (2) help the NOAA/NWS Office of Water Prediction develop continental scale channel size and shape estimates to improve flood prediction and hydraulic routing and to (3) bolster the co-agency sponsored National Hydrologic Geospatial Fabric (Bock 2022; Blodgett et al. 2021; Blodgett, Johnson, and Bock 2023).

Example of use

AHGestimation is available on Gtithub and can be installed as follows:

```
#install.packages(remotes)
remotes::install.packages("mikejohnson51/AHGestimation")
```

This example shows how the package can be used to (1) remove data outliers based on time criteria and an NLS envelope (2) fit AHG parameters using a hybrid modeling approach and (3) estimate and plot the shape of the associated cross-section with an area-depth relation. The script to generate the plot can be

found here, and the `nwis` data object is exported with the package to provide sample data and contains the field measurements taken at USGS site 01096500 on the Nashua River at East Pepperell in Massachusetts.

```
nwis

#> siteID      date      Q      Y      V      TW
#> 01096500 1984-11-14  9.7409954 0.5276645 0.652272 28.34640
#> 01096500 1985-01-04 11.8930757 0.6263473 0.682752 27.73680
#> 01096500 1985-05-06 10.8170356 0.5952226 0.563880 32.30880
#> 01096500 1985-06-26  1.9453674 0.2400300 0.332232 24.38400
#> 01096500 1986-01-09 11.3550556 0.5920154 0.606552 31.69920
#> 01096500 1986-02-27 21.4358532 0.8574593 0.902208 27.73680
#> 01096500 1986-05-22  6.9093107 0.4806462 0.454152 31.69920
#> 01096500 1986-07-07  8.9198068 0.5457371 0.512064 32.00400

nrow(nwis)
#> 245

# Keep only those observation made in the most recent 10 years,
# and that fall within the .5 nls envelope
(data = nwis |>
  date_filter(10, keep_max = TRUE) |>
  nls_filter(allowance = .5) )

# data reduced to 80 observations based on filters
nrow(data)
#> 80
```

The reduced clean data can then be used to fit an AHG relation and compute a set of hydraulic parameters:

```
# Fit AHG relations
ahg_fit = ahg_estimate(data)
t(ahg_fit[1,])

#> V_method  "nls"
#> TW_method "nls"
#> Y_method  "nls"
#> viable    "TRUE"
#> tot_error "0.352759"
#> V_error   "0.1470922"
#> TW_error  "0.1161101"
#> Y_error   "0.08955664"
#> V_coef    "0.2822548"
#> TW_coef   "18.17896"
#> Y_coef    "0.1945348"
#> V_exp     "0.3105107"
#> TW_exp    "0.1850407"
#> Y_exp     "0.5087359"
#> condition "bestValid"

# Use the AHG relations to compute hydraulic parameters
shape = compute_hydraulic_params(ahg_fit[1,])

#>      r      p      d      R      bd      fd      md
#> 2.749318 0.6103574 5.427385 1.363727 0.1842508 0.5065641 0.3091851
```

Finally, the max width and depth, paired with the derived r coefficient can be used to generate a cross section:

```
# Use the max width, max depth, and derived `r` to generate a cross section
# x: is the relative distance from the left bank
# Y: is the associated depth
# A: is the area associated with depth Y

cs = cross_section(r = shape$r,
                  TW = max(data$TW),
                  Ymax = max(data$Y))

#>   ind      x      Y      A
#>   1 0.000000 3.5656665613 1.318953e+02
#>   2 1.040816 3.1871221498 1.130112e+02
#>   3 2.081633 2.8351885546 9.618829e+01
#>   4 3.122449 2.5090304653 8.127753e+01
#>   5 4.163265 2.2078034104 6.813466e+01
#>   6 5.204082 1.9306532333 5.662032e+01
#>   7 6.244898 1.6767155105 4.660008e+01
#>   8 7.285714 1.4451149046 3.794447e+01
#>   9 8.326531 1.2349644401 3.052910e+01
#>  10 9.367347 1.0453646866 2.423471e+01
```

As a proof of concept, this approach was applied to the synthetic rating curves generated by NOAA/NWS OWP’s inundation mapping software ((Water Prediction 2023)). The package allowed the size of their rating curve database to be reduced by 99.68% and maintained average accuracy within 0.4% nRMSE or the source data (J. ; C. Johnson J. M.; Coll 2022). Further, the reduction to a consistent AHG formulation allows them to be more interoperable with efforts like (Enzinger, Minear, and Livneh 2023), or (Afshari 2019) while also beginning to provide key training data for more advanced prediction methods that seek to estimate the shape on non-measured river segments.

Acknowledgements

The development of this package began in 2017 following the NOAA/NWS OWP Summer Institute and clear evidence channel shape may be a limiting factor in National Water Model performance.

The algorithm and implementation began as a graduate school project between friends at UC Santa Barbara and UMass Amherst and has since evolved to provide an open source utility for robust large scale data synthesis and evaluation. Funding from the National Science Foundation (Grants 1937099, 2033607) provided time to draft (J. ; C. Johnson J. M.; Coll 2022) and apply an early version of this software to the Continental Flood Inundation Mapping synthetic rating curve dataset (Liu and Maidment 2020). Funding from the NOAA/NWS OWP supported the addition of data filtering and hydraulic geometry estimation, improved documentation, and code hardening. We are grateful to all involved.

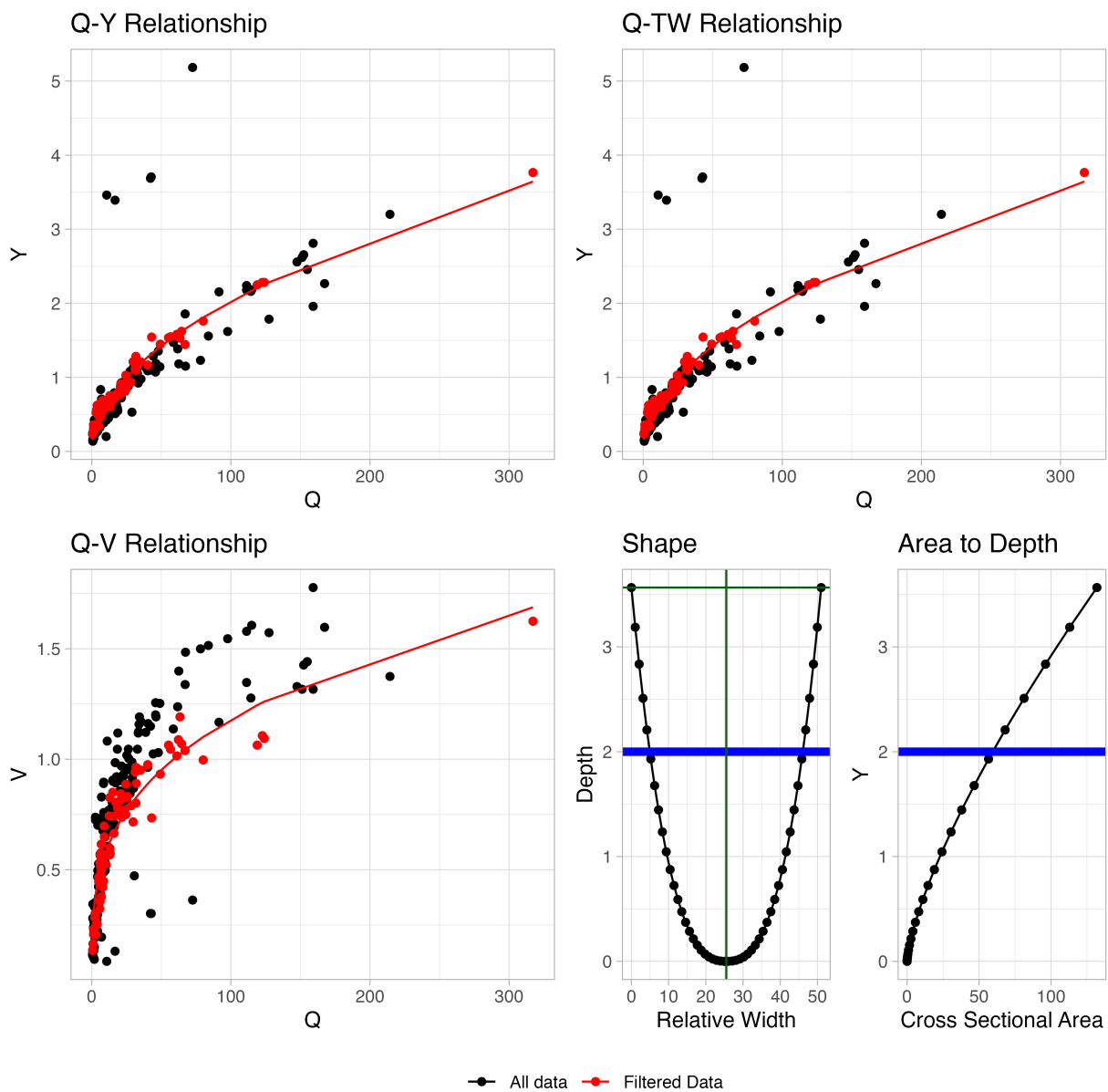


Figure 1: Faceted image with multiple views of the channel estimate.

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