# **Primary References for Hydrologic Research Leading to the National Water Model (NWM) and Height Above Nearest Drainage (HAND) Computational Systems**

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## **National Water Model (NWM)**

**Precipitation forecast model forcings for NWM**

*See* [*http://www.nco.ncep.noaa.gov/pmb/products/*](http://www.nco.ncep.noaa.gov/pmb/products/) *and* [*http://nomads.ncep.noaa.gov/*](http://nomads.ncep.noaa.gov/) *for further details.*

* National Severe Storms Laboratory MRMS (Multi-radar Multi-sensor) precipitation analysis (gridded 1km product), see <https://www.nssl.noaa.gov/projects/mrms/>.
* WRF High Resolution Rapid Refresh (HRRR) Numerical Weather Prediction Model (3km resolution), see <http://www.nco.ncep.noaa.gov/pmb/products/hrrr/>.
* Global Forecast System (GFS Numerical Weather Prediction Model, 13km resolution, regridded to 1km), see <http://www.nco.ncep.noaa.gov/pmb/products/gfs/>.
* Climate Forecast System (CFS Numerical Weather Prediction Model, 50km resolution, downscaled and bias corrected to 1km), see <http://www.nco.ncep.noaa.gov/pmb/products/cfs/>.

**WRF-Hydro (Weather Research and Forecasting – Hydrologic Model) to estimate runoff from precipitation**

*See* [*https://ral.ucar.edu/projects/wrf\_hydro/*](https://ral.ucar.edu/projects/wrf_hydro/) *for further details.*

Gochis, D.J., W. Yu, D.N. Yates, 2015: The WRF-Hydro model technical description and user's guide, version 3.0. NCAR Technical Document. 123 pages.

Kerandi, N., J. Arnault, P. Laux, S. Wagner, J. Kitheka, and H. Kunstmann, 2017: Joint atmospheric-terrestrial water balances for East Africa: a WRF-Hydro case study for the upper Tana River basin. *Theoretical and Applied Climatology*, doi: 10.1007/s00704-017-2050-8.

Verri, G., N. Pinardi, D. Gochis, J. Tribbia, A. Navarra, G. Coppini, and T. Vukicevic, 2017: A meteo-hydrological modelling system for the reconstruction of river runoff: the case of the Ofanto river catchment. *Natural Hazards and Earth System Sciences*, 17, 1741-1761, doi:10.5194/nhess-17-1741-2017.

Powers, J. G., and Coauthors, 2017: The Weather Research and Forecasting Model: Overview, system efforts, and future directions. *Bulletin of the American Meteorological Society*, 98, 1717-1737, doi:10.1175/BAMS-D-15-00308.1.

Li, L., D. J. Gochis, S. Sobolowski, and M. D. S. Mesquita, 2017: Evaluating the present annual water budget of a Himalayan headwater river basin using a high-resolution atmosphere-hydrology model. *Journal of Geophysical Research: Atmospheres*, 122, 4786-4807, doi:10.1002/2016JD026279.

Cuntz, M., J. Mai, L. Samaniego, M. Clark, V. Wulfmeyer, O. Branch, S. Attinger, and S. Thober, 2016: The impact of standard and hard-coded parameters on the hydrologic fluxes in the Noah-MP land surface model. *Journal of Geophysical Research: Atmospheres*, 121, 10,676-10,700, doi:10.1002/2016JD025097.

Senatore, A., G. Mendicino, D. J. Gochis, W. Yu, D. Yates, and H. Kunstmann, 2015: Fully coupled atmosphere-hydrology simulations for the central Mediterranean: Impact of enhanced hydrological parameterization for short and long time scales. *Journal of Advances in Modeling Earth Systems*, 7, 1693-1715, doi:10.1002/2015MS000510.

Clark, M., and Coauthors, 2015: Improving the representation of hydrologic processes in Earth System Models. Water Resources Research, 51, 5929-5956, doi:10.1002/2015WR017096.

Yucel, I., A. Onen, K. K. Yilmaz, and D. J. Gochis, 2015: Calibration and evaluation of a flood forecasting system: Utility of numerical weather prediction model, data assimilation and satellite-based rainfall. *Journal of Hydrology*, 523, 49-66, doi:10.1016/j.jhydrol.2015.01.042.  
  
Bierkens, M. F. P., and Coauthors, 2015: Hyper-resolution global hydrological modelling: What is next? *Hydrological Processes*, 29, 310-320, doi:10.1002/hyp.10391.  
  
Salas, Fernando R., Marcelo A. Somos-Valenzuela, Aubrey Dugger, David R. Maidment, David J. Gochis, Cédric H. David, Wei Yu, Deng Ding, Edward P. Clark, and Nawajish Noman (2017), Towards Real-Time Continental Scale Streamflow Simulation in Continuous and Discrete Space. *JAWRA Journal of the American Water Resources Association*, 1-21. DOI: 10.1111/1752-1688.12586

**RAPID (Routing Application for Parallel computatIon of Discharge) to estimate streamflow throughout the river network from surface and subsurface runoff**

*See* [*http://rapid-hub.org/*](http://rapid-hub.org/) *for further details.*

David, Cédric H., David R. Maidment, Guo-Yue Niu, Zong- Liang Yang, Florence Habets and Victor Eijkhout (2011), River network routing on the NHDPlus dataset, *Journal of Hydrometeorology*, 12(5), 913-934. DOI: 10.1175/2011JHM1345.1

David, Cédric H., James S. Famiglietti, Zong-Liang Yang, Florence Habets, and David R. Maidment (2016), A Decade of RAPID – Reflections on the Development of an Open Source Geoscience Code, *Earth and Space Science*, 3, 1-19, DOI: 10.1002/2015EA000142.

*RAPID software citation:*

David, Cédric H. (2013), RAPID v1.4.0, Zenodo, DOI: 10.5281/zenodo.24756.

*For the use of RAPID in the National Flood Interoperability Experiment (next three):*

Lin, P., M.A. Rajib, Z.-L. Yang, M.A.S.-Valenzuela, V. Merwade, D.R. Maidment, Y. Wang, L. Chen, 2017: Spatio-temporal evaluation of simulated evapotranspiration and streamflow over Texas using the WRF-Hydro-RAPID framework. *Journal of American Water Resource Association*, 1-21. DOI: 10.1111/1752-1688.12585.

Salas, Fernando R., Marcelo A. Somos-Valenzuela, Aubrey Dugger, David R. Maidment, David J. Gochis, Cédric H. David, Wei Yu, Deng Ding, Edward P. Clark, and Nawajish Noman (2017), Towards Real-Time Continental Scale Streamflow Simulation in Continuous and Discrete Space. *JAWRA Journal of the American Water Resources Association*, 1-21. DOI: 10.1111/1752-1688.12586

Snow, Alan D., Scott D. Christensen, Nathan R. Swain, James Nelson, Daniel P. Ames, Norman L. Jones, Deng Ding, Nawajish Noman, Cédric H. David, and Florian Pappenberger (2016), A Cloud-Based High-Resolution National Hydrologic Forecast System Downscaled from a Global Ensemble Land Surface Model, *Journal of the American Water Resources Association*, 1-15, DOI: 10.1111/1752-1688.12434.

**National Water Model (NWM)**

*See* [*http://water.noaa.gov/about/nwm*](http://water.noaa.gov/about/nwm) *for further details;* [*http://water.noaa.gov/map*](http://water.noaa.gov/map) *for forecasts. An in-depth overview article is not yet available for the NWM, but here are some overview materials (next three):*

Kopp, S. and S. Fox, Ed’s, 2018. Theme issue on The National Water Model, *Water Resources IMPACT, 20:1,* January 2018. American Water Resources Association. <http://www.awra.org/impact/issues/Jan2018IMPACT.pdf>

Cosgrove, B., D. J. Gochis, T. Graziano, E. Clark, and T. Flowers, 2018. An Update on the NOAA National Water Model and Related Activities. *American Meteorological Society 32nd Conference on Hydrology*, January 10, 2018. <https://ams.confex.com/ams/98Annual/webprogram/Paper332874.html>

Cosgrove, B., D. J. Gochis, E. Clark, Z. Cui, A. Dugger, X. Feng, L. Karsten, S. Khan, D. Kitzmiller, H. Lee, Y. Liu, J. McCreight, A. J. Newman, A. Oubeidillah, L. Pan, C. Pham, F. Salas, K. Sampson, G. Sood, A. W. Wood, D. Yates, and W. Yu, 2017. Continental-Scale Operational Hydrologic Modeling: Version 1.0 of the National Water Model, *American Meteorological Society 31st Conference on Hydrology*, January 23, 2017. <https://ams.confex.com/ams/97Annual/webprogram/Paper314045.html>

*There are many additional AMS and AGU talks on the NWM from NOAA Office of Water Prediction and NCAR which are available, covering various aspects of the NWM along with its performance.*

## **Height Above Nearest Drainage (HAND)**

**TauDEM: to compute a specialized elevation model (HAND) for hydrologic analysis**

*See* [*http://hydrology.usu.edu/taudem/taudem5/*](http://hydrology.usu.edu/taudem/taudem5/) *for further details.*

Fan, Y., Y. Liu, S. Wang, D. Tarboton, A. Yildirim, and N. Wilkins-Diehr, 2014. Accelerating TauDEM as a Scalable Hydrological Terrain Analysis Service on XSEDE. In: *Proceedings of the 2014 Annual Conference on Extreme Science and Engineering Discovery Environment*, Atlanta, GA, USA, July 13-18. ACM, New York. DOI: 10.1145/2616498.2616510

Survila, K., A.A. Yildirim, T. Li, Y. Liu, D.G. Tarboton, and S. Wang, 2016. A Scalable High-performance Topographic Flow Direction Algorithm for Hydrological Information Analysis. In: *Proceedings of the 2016 Annual Conference on Extreme Science and Engineering Discovery Environment (XSEDE’16)*. Miami, Florida. July 17-21. ACM, New York, pp. 11:1—11:7. DOI: 10.1145/2949550.2949571

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water resources research* 33(2): 309-319. DOI: 10.1029/96WR03137

*David Tarboton comment for next 3 references: considers Tesfa et al. 2011 as somewhat definitive because it frames many proximity measures in a general way and provides a general approach to their evaluation.  HAND is equivalent to vertical distance down to an arbitrary target, with the target being a stream.  It is thus a special case of a general idea.  This paper represents the end point in a logical line of development followed by Tarboton and Baker 2008 and Tarboton et al. 2009.*

Tarboton, D.G. and M.E. Baker, 2008. Towards an algebra for terrain-based flow analysis. In: *Representing, modeling and visualizing the natural environment: innovations in GIS* 12, NJ Mount, GL Harvey, P. Aplin and G. Priestnall (Editors). CRC Press, Florida. Pp: 167-194. DOI: 10.1201/9781420055504.ch12

Tarboton, D. G., K. A. T. Schreuders, D. W. Watson, and M. E. Baker, 2009. Generalized terrain-based flow analysis of digital elevation models. In:*18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation*, July 2009. R. S. Anderssen, R. D. Braddock and L. T. H. Newham (Editors). Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, pp. 2000-2006. URL: <http://www.mssanz.org.au/modsim09/F4/tarboton_F4.pdf>

Tesfa, Teklu K., David G. Tarboton, Daniel W. Watson, Kimberly A.T. Schreuders, Matthew E. Baker, and Robert M. Wallace, 2011. Extraction of hydrological proximity measures from DEMs using parallel processing, *Environmental Modelling & Software* 26(12): 1696-1709. DOI: 10.1016/j.envsoft.2011.07.018.

Yildirim, A.A., D.G. Tarboton, Y. Liu, N.S. Sazib, S. Wang, 2016. Accelerating TauDEM for Extracting Hydrology Information from National-Scale High Resolution Topographic Dataset. In: *Proceedings of the 2016 Annual Conference on Extreme Science and Engineering Discovery Environment (XSEDE’16)*. Miami, Florida. July 17-21. ACM, New York, pp. 3:1—3:2. DOI: 10.1145/2949550.2949582

*A high-resolution topography review:*

Passalacqua, P., P. Belmont, D. M. Staley, J. D. Simley, J. R. Arrowsmith, C. A. Bode, C. Crosby, S. B. DeLong, N. F. Glenn, S. A. Kelly, D. Lague, H. Sangireddy, K. Schaffrath, D. G. Tarboton, T. Wasklewicz and J. M. Wheaton, (2015), “Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review,” Earth-Science Reviews, 148: 174-193, <http://dx.doi.org/10.1016/j.earscirev.2015.05.012>.  <http://hydrology.usu.edu/dtarb/Passalacqua_2015.pdf>

*Prior work that first presented the height above nearest neighbor idea (next 4 references):*

Rodda, H. J. E., (2005), “The Development and Application of a Flood Risk Model for the Czech Republic,” Natural Hazards, 36(1): 207-220, <http://dx.doi.org/10.1007/s11069-004-4549-4>.

Rennó, C. D., A. D. Nobre, L. A. Cuartas, J. V. Soares, M. G. Hodnett, J. Tomasella and M. J. Waterloo, (2008), “HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia,” Remote Sensing of Environment, 112(9): 3469-3481, <http://doi.org/10.1016/j.rse.2008.03.018>.

Nobre, A. D., L. A. Cuartas, M. Hodnett, C. D. Rennó, G. Rodrigues, A. Silveira, M. Waterloo and S. Saleska, (2011), “Height Above the Nearest Drainage – a hydrologically relevant new terrain model,” Journal of Hydrology, 404(1–2): 13-29, <http://dx.doi.org/10.1016/j.jhydrol.2011.03.051>.

Nobre, A. D., L. A. Cuartas, M. R. Momo, D. L. Severo, A. Pinheiro and C. A. Nobre, (2016), “HAND contour: a new proxy predictor of inundation extent,” Hydrological Processes, 30(2): 320-333, <http://dx.doi.org/10.1002/hyp.10581>.

**GeoNet: Geomorphic feature extraction**

*Computational tool for the automatic extraction of channel networks and channel heads from high resolution topography, such as Lidar. See* [*https://sites.google.com/site/geonethome/*](https://sites.google.com/site/geonethome/) *for further details.*

Sangireddy, H., C.P. Stark, A. Kladzyk, P. Passalacqua (2016), GeoNet: An open source software for the automatic and objective extraction of channel heads, channel network, and channel morphology from high resolution topography data, Environmental Modeling and Software, 83, 58-73, doi:10.1016/j.envsoft.2016.04.026.

Passalacqua, P. and E. Foufoula-Georgiou (2015), Comment on "Objective extraction of channel heads from high-resolution topographic data" by Fiona J. Clubb et al., Water Resources Research, 51, 2, 1372-1376, doi:10.1002/2014WR016412.

Passalacqua, P., P. Belmont, E. Foufoula-Georgiou (2012), Automatic geomorphic feature extraction from lidar in flat and engineered landscapes, Water Resources Research, 48, 3, W03528, doi:10.1029/2011WR010958.

Passalacqua, P., P. Tarolli, E. Foufoula-Georgiou (2010), Testing space-scale methodologies for automatic geomorphic feature extraction from lidar in a complex mountainous landscape, Water Resources Research, 46, W11535, doi:10.1029/2009WR008812.

Passalacqua, P., T. Do Trung, E. Foufoula-Georgiou, G. Sapiro, W. E. Dietrich (2010), A geometric framework for channel network extraction from lidar: Nonlinear diffusion and geodesic paths, Journal of Geophysical Research Earth Surface, 115, F01002, doi:10.1029/2009JF001254.

**HAND for Continental USA based on USGS National Elevation Dataset (NED, 10m resolution)**

*See* [*https://web.corral.tacc.utexas.edu/nfiedata/*](https://web.corral.tacc.utexas.edu/nfiedata/) *for downloadable HAND datasets of continental USA, and some tools for visualizing and working with it.*

Liu, Yan Y., David R. Maidment, David G. Tarboton, Xing Zheng, Shaowen Wang. 2018. A CyberGIS Integration and Computation Framework for High-Resolution Continental-Scale Flood Inundation Mapping. *Journal of the American Water Resources Association*. Accepted.

Liu, Y.Y., Maidment, D.R., Tarboton, D.G., Zheng, X., Yildirim, A., Sazib, N.S., and Wang, S. 2016. A CyberGIS Approach to Generating High-resolution Height Above Nearest Drainage (HAND) Raster for National Flood Mapping. *The Third International Conference on CyberGIS and Geospatial Data Science*. July 26–28, 2016, Urbana, Illinois. doi:10.13140/RG.2.2.24234.41925/1

From Yan Liu: Please refer to our code at <https://github.com/cybergis/nfie-floodmap/blob/master/test/huc6tms.sh> to see how [WTMS](https://www.opengeospatial.org/standards/wmts) tiles are generated for all HUC6 HAND rasters.

**HAND-based inundation mapping for local and regional areas based on high-resolution Lidar**

*Further research is underway for Lidar-based HAND and floodplain mapping.*

Zheng, X., Maidment, D. R., Tarboton, D. G., Liu, Y. Y., & Passalacqua, P. (2018). GeoFlood: Large‐Scale Flood Inundation Mapping Based on High‐Resolution Terrain Analysis. *Water Resources Research*, 54(12), 10-013.

Zheng, X., Tarboton, D. G., Maidment, D. R., Liu, Y. Y., & Passalacqua, P. (2018). River channel geometry and rating curve estimation using height above the nearest drainage. *JAWRA Journal of the American Water Resources Association*, 54(4), 785-806.

Liu, Y. Y., Maidment, D. R., Tarboton, D. G., Zheng, X., & Wang, S. (2018). A CyberGIS integration and computation framework for high‐resolution continental‐scale flood inundation mapping. *JAWRA Journal of the American Water Resources Association*, 54(4), 770-784.

*Email from David Tarboton, 2019-11-17: Obstacle removal has to happen before Pit Removal.  See Fig 3 in Yan’s JAWRA paper (A CyberGIS integration, etc., 2018, above).  Also, there are details of Obstacle Removal that need to be spelled out.  Yan had this dashed in his workflow diagram as it was not implemented in the layer he produced. See the section on flow direction conditioning in:*

Garousi‐Nejad, I., Tarboton, D. G., Aboutalebi, M., Torres‐Rua, A. F. (2019). Terrain Analysis Enhancements to the Height Above Nearest Drainage Flood Inundation Mapping Method. AGU Water Resources Research, 55(10), 7927-8269, October 2019. <https://doi.org/10.1029/2019WR024837>

*There are scripts that detail the methods in*

<https://www.hydroshare.org/resource/7235a0d6a18343078b2028085b7d8018/>

*I think that a refresh of the HAND layer that includes obstacle removal using this process would be a useful incremental improvement over the current National Hand layer in use.*

*David R. Maidment’s NWM-HAND Log: The purpose of this information page is to provide links to information about the National Water Model and the technical foundation on which it has been constructed.*

http://www.ce.utexas.edu/prof/maidment/NWM.htm

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