Technical Description of the National Water Model Implementation WRF-Hydro

Developed by large integrated NWC, NCAR and academic development team

• Review current National Water Model configuration
  – Model setup
  – Forcing data preparation
  – Current output products
• Overview of Rwrfhydro evaluation and verification system
• Results to date (retrospective and operational runs)
• NWM v1.1 Calibration Procedure
• Summary
Goals of Version 1 of the National Water Model

- Operational forecast streamflow guidance for currently underserved locations
- Spatially continuous estimates and forecasts of hydrologic states for the nation through, enhanced physical accounting of major water cycle components (snowpack, soil moisture, channel flow, major reservoir inflows, flood inundation)
- Seamlessly interface real-time hydrologic products into and advanced geospatial intelligence framework
- Implement an Earth system modeling architecture that permits rapid model evolution of new data, science and technology
National Water Model (NWM) Core: WRF-Hydro

- WRF-Hydro forms the foundation of the National Water Model
- A community-based, robust Earth System Modeling Framework (ESMF)-compliant hydrologic modeling framework supported by the National Center for Atmospheric Research (NCAR) being put into operations by an OWP, NCAR and National Centers for Environmental Prediction (NCEP) partnership
- Not dependent on a particular forcing data source or choice of LSM
- Able to operate over multiple scales and with multiple physics options

IOC System Flow

1. NWM Forcings Engine (NWS numerical weather models and observations)
2. NoahMP LSM (1 km grid)
3. Terrain Routing Module (250 m grid)
4. NHDPlus Catchment Aggregation (avg. size ~1mi²)
5. Channel & Reservoir Routing Modules

Forecasts
# NWM Operational Configuration

Running Continuously on WCOSS since May 9th

<table>
<thead>
<tr>
<th></th>
<th>Analysis &amp; Assimilation</th>
<th>Short-Range</th>
<th>Medium-Range</th>
<th>Long-Range</th>
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<tr>
<td><strong>Cycling Frequency</strong></td>
<td>Hourly</td>
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<td><strong>Forecast Duration</strong></td>
<td>- 3 hours</td>
<td>0-15 hours</td>
<td>0-10 days</td>
<td>0-30 days</td>
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<td><strong>Forecast Latency</strong></td>
<td>1 hour</td>
<td>1 hour 45 mins</td>
<td>6 hours</td>
<td>19 hours</td>
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<td><strong>Meteorological Forcing</strong></td>
<td>MRMS blend/ HRRR/RAP bkgn.</td>
<td>Downscaled HRRR/RAP blend</td>
<td>Downscaled GFS</td>
<td>Downscaled &amp; bias-corrected CFS</td>
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<td><strong>Spatial Discretization &amp; Routing</strong></td>
<td>1km/250m/NHDPlus Reach</td>
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<td><strong>Assimilation of USGS Obs</strong></td>
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| **Reservoirs**           |                         |             |              |            | (1260 water bodies parameterized with level pool scheme)
• ~180 possible ‘physics’ component configurations for streamflow prediction:
  – 3 up-to-date column physics land models (Noah, NoahMP, CLM-old)
  – 3 overland flow schemes (Diffusive Wave, Kinematic Wave, Direct basin aggregation)
  – 4 lateral/baseflow groundwater schemes (Boussinesq shallow-saturated flow, 2d aquifer model, Direct Aggregation Storage-Release: pass-through or exponential model)
  – 5 channel flow schemes: Diffusive wave, Kinematic Wave, RAPID-Muskingam for NHDPlus, Custom Network Muskingam/Muskingam Cunge

• Simple level-pool reservoir with management

• DART, filter-based hydrologic data assimilation (James)
National Water Model
Version 1.0: Model Chain

1. NWM Forcing Engine
   (1 km grid)

2. NoahMP LSM
   (1 km grid)

3. Terrain Routing Module
   (250 m grid)

4. NHDPlus Catchment Aggregation
   (2.7M unique catchments and river reaches)

5. Channel & Reservoir Routing Modules

NWM uses NCAR supported community WRF-Hydro system
NWM: http://water.noaa.gov/about/nwm
WRF-Hydro: https://www.ral.ucar.edu/projects/wrf_hydro
National Water Model
Version 1.0: Model Chain
(Long Range Configuration)

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5. Channel & Reservoir Routing Modules

Forecast Products
Operational Cycling of the National Water Model

**Dynamic Inputs**
- Resident Radar & NWP Data (WCOSS)
- Quality ranked real-time USGS streamflow data

**Forcing Data Engine**
- Analysis & Assimilation
- Short Range
- Medium Range
- Long Range

**WRF-Hydro Model**
- Analysis & Assimilation
- Short Range
- Medium Range
- Long Range

**‘Static’ Inputs**
- Forcing Engine Static Data
  - Weight files
  - Terrain fields
  - Bias correction fields
- WRF-Hydro Static Data
  - Model config. files
  - Re-gridding weight files
  - Distributed parameters
National Water Model v1.0
Meteorological Forcing Data Engine
1. Create national 1km gridded fields of:
   - Temperature, mixing ratio, surface pressure, u-, v-windspeed, longwave and shortwave radiation, precipitation rate

2. Terrain Downscaling of:
   - Temperature (NARR distributed climatological lapse rate)
   - Mixing ratio (conserve RH)
   - Surface pressure
   - Incoming shortwave radiation (terrain slope and aspect)

3. Open source ncl/bash scripted workflow utilizing ESMF regridding tools,

4. Rwrfhydro-ESMF regridding used for evaluation
Upcoming Meteorological Forcing Enhancements:

Now:

• Ongoing ‘hydro-centric’ analysis of operational precipitation analyses (QPE) and forecasts (QPF)
  • A. RafieeiNasab & L. Pan (NCAR): MRMS/HRRR blend and NLDAS verification
  • X. Feng (OWP/NWC): Short Range/HRRR
  • H. Lee (OWP): Medium range/GFS
  • Y. Lu (OWP): Long range/CFS
  • Using hourly and daily Stage IV and HADS station data for verification

• Expand bias corrections to Short, Medium range forecasts (exists in Analysis and Assimilation and Long range)

• Improved characterization of rain/snow partitioning
Assessment of how much errors in QPF contribute to errors in streamflow

- Preliminary analyses show some agreement, particularly in places where QPE bias is high
- Many locations out west have differential error structures highlighting need for hydro model calibration
National Water Model v1.0 Physics and Related Products (Operational and Experimental)
Model Setup:

- NHDPlusV2-Encompassing Domain
- 1km NoahMP land model:
  - USGS-NLCD land cover (2011)
  - NRCS STATSGO, 1km soils
  - Climatological vegetation structure (v1.0)
- 250m routing
  - Diffusive wave overland flow
  - Saturated subsurface flow
  - NHDPlusv2 catchment-based baseflow parameterization
- NHDPlusv2 channel routing
  - Muskingum-Cunge
  - oCONUS manual reach processing....
  - 2.7M river reaches
  - 1260 passive, level-pool reservoirs
NoahMP Column Physics:

- Precipitation
- Condensation
- Runoff
- Evaporation
- Transpiration
- Direct Soil Evaporation
- Canopy Water Evaporation
- Turbulent Heat Flux to/from Snowpack/Soil/Plant Canopy
- Deposition/Sublimation to/from snowpack
- Snowmelt
- Soil Heat Flux
- Soil Moisture Flux
- Interflow
- Internal Soil Moisture Flux
- Gravitational Flow
Overland Flow Routing:

- Pixel-to-pixel routing
  - Steepest descent or 2d
  - Diffusive wave/backwater permitting
  - Explicit solution

- Ponded water (surface head) is fully-interactive with land model, provides ‘local inundation’ estimation

- Sub-grid variability of ponded water on routing grid is preserved between land model calls

Adapted from: Julian et al, 1995 – CASC2D, GSSHA
Subsurface Routing:

- Quasi steady-state, Boussinesq saturated flow model
- Exfiltration from fully-saturated soil columns
- Anisotropy in vertical and horizontal Ksat
- No ‘perched’ flow
- Soil depth is uniform in v1.0 but will vary in future versions

Adapted from: Wigmosta et. al, 1994
National Water Model v1.0 Physics Configuration

Land Surface Model Outputs:

National Water Model Soil Moisture (Experimental)
Analysis valid for 2016-05-26 11:00:00 UTC
Model initialized at 2016-05-26 08:00:00 UTC
Land Surface Model Outputs:

Snow Water Equivalent (SNEQV): Being validated with SNOTEL, MODIS SCA, SNODAS, NASA-Airborne Lidar
Being validated against Ameriflux ET and ‘synthesis’ ET products
Land Surface Model Outputs

Depth of local ponded water
Land Surface Model Outputs

Depth to soil saturation (‘shallow water table’): May 24, 2015
Conceptual Baseflow ‘Bucket’ models:

- Gridded runoff terms (soil drainage and channel inflow) get aggregated into NHDPlus catchments
- 2-parameter exponential model
- Bucket discharge gets added to corresponding NHDPlus channel reach
Channel Hydraulics:

• **Reach/vector-based:**
  - Version 1.0 uses Muskingum-Cunge (fast and stable)
  - *Future versions are utilizing hydraulic methods*

  ![Diagram](image)

  - Surface water on channel grid cells get deposited in channel as ‘lateral inflow’
  - One-way over flow into channel
  - No sub-surface losses
  - ‘Infinite’ channel depth (no overbank flow)

• **Channel Parameters:**
  - A priori function of Strahler order
  - Trapezoidal channel (bottom width, side slope)
Seamless Simulation of Nation’s Hydrologic System

Legend
Streamflow (cfs)
- 0 - 119
- 119 - 7,520
- 7,521 - 88,700
- 88,701 - 201,900
- 201,901 - 460,000
- 460,001 - 1,200,000

05/01/2015 00:00

Seamless Simulation of Nation’s Hydrologic System
- **Rwrfhydro-generated hydrograph products**
- Forecasts from Short, Medium and Long Range configuration
- De facto time-lagged ensembles
Issues with NHDPlus Channels: Survey dependent channel definition artifacts: tends to affect Order 1 and 2 streams...

Other Issues:
- Broken links
- Incorrect topologies
- International borders
Nudging-based Data Assimilation:

- Lots of available observations from USGS NWIS
  - 2015:
    - 6,000 – 8,000 available stations (.2-.3% of NHD reaches)
    - 15,000,000 – 25,000,000 observations monthly
- State Agencies...
- Why nudging?
  - Calibration challenges => model biases => improper error covariances
    - (No error covariances => treat symptom not cause)
  - Computationally tractable at national scale
  - Future: hybrid with other DA methods

**National Water Model v1.0 Physics Configuration**
Lakes & Reservoirs:

- 1,260 NHDPlus water bodies > 0.75 sq. km
- Specified spillway characteristics (length, height)

Level Pool Scheme:

- 3 ‘passive’ discharge mechanisms:
  - Orifice flow
  - Spillway flow
  - Direct Pass-through

Output variables:

- Inflow (cms)
- Outflow (cms)
- Water level elevation (m-MSL)

v2 will have capability for time varying specification of discharge
Lakes & Reservoirs:

- 1,260 NHDPlus water bodies > 0.75 sq. km
- Specified spillway characteristics (length, height)

New Development:

- More reservoirs
- Great Lakes System
- Bathymetry for elevation-area-volume specification
- Discharge Options Under Development:
  - Fixed/constant value
  - Operating Curves
  - Downstream stream gauge data assimilation
  - Management schedule

Future:

- Diversions
- Reservoir evaporation
- Irrigation
NWM V1.0 Output

- **Hydrologic Output**
  - River channel discharge and velocity at 2.7 million river reaches
  - Reservoir inflow, outflow, elevation
  - Ponded water depth and depth to saturation (250 m CONUS+ grid)

- **Land Surface Output**
  - 1km CONUS+ grid
  - Soil and snow pack states
  - Energy and water fluxes

- **Direct-output and derived products** (e.g. stream flow anomalies)

- **Data Services**
  - Public-facing NWC website (animation, zoom, point and click hydrographs)
  - Data feed to River Forecast Centers
  - NOMADS data service (NOAA National Operational Model Archive & Distribution System)
WRF-Hydro/National Water Model Evaluation, Verification and Visualization Tools
Rwrfhydro: R package for WRF-Hydro Model Evaluation

https://github.com/mccreigh/rwrfhydro

- Set of R tools to support WRF-Hydro pre- and post-processing
- Open source, community tool
- Full documentation and training vignettes
- Major Features:
  - Domain visualization
  - Remote sensing & geospatial data prep
  - Output post-processing
  - Observation data acquisition and processing
  - Model output evaluation and visualization
  - Generally model agnostic
- Developed in parallel with NWM v1.0
Initial Retrospective NWM CONUS Evaluations:

<table>
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<tr>
<th>Run</th>
<th>Time Period</th>
<th>Forcing</th>
<th>Resolution</th>
<th>Physics</th>
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<tbody>
<tr>
<td>5YR_NORT</td>
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Initial evaluation focused on:

- Precipitation at ~5700 HADS stations
- Streamflow at ~1300 GAGES-II reference basins
- Streamflow at a sample of ~15 “big” rivers
- Snow at ~800 SNOTEL stations (and SNODAS)
- ET at ~130 Ameriflux stations (and ET products)
- Soil Moisture at USDA SCAN stations (anomaly correlations)
# Rwrfhydro: R package for WRF-Hydro Model Evaluation

[https://github.com/mccreigh/rwrfhydro](https://github.com/mccreigh/rwrfhydro)

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Initial Retrospective NWM CONUS Evaluations: Streamflow

Average Daily Streamflow Correlation Over Gages II Unregulated Basins (approx. 1,000) Simulation With NLDAS2 Forcing, v1.0 Parameters, No Data Assimilation (Oct 2011 - Feb 2016)

Correlation:

Bias:

74% of basins have correlation > 0.6

35% of basins have bias < 20%

Mean Flowrate (cms)

[Map showing correlation and bias with color-coded dots representing site counts and distributions of daily correlation and bias]
Regional Breakouts of Big River Flows:

Promising initial results: Simulated flows closely resemble actual flow where flow is unregulated
Short Range Prediction Goal:
Provide effective guidance for floods and flash floods

Assess skill of forecast peak flow amount and timing

Based on 40 days of NWM forecasts from WCOSS versus ~1000 USGS Gauges II unregulated stations, May-June 2016

Preliminary Findings

- Errors in peak flow amount center around 0, and are relatively small (i.e., ≤5 cms)
- Median errors in peak flow timing are generally under ~2 hours

Pre-operational Short Range (0-15 hrs) Verification
Medium Range Prediction Goal:
Provide advanced lead-time guidance for flood and river flow

Assess forecast daily flow correlation and percent bias

Based on 71 days of NWM forecasts from WCOSS versus ~1000 USGS Gauges II unregulated stations, May-June 2016

Preliminary Findings
• Though trailing off with time, daily precipitation correlation values are skillful through 10 days
• Streamflow over all 10 days in most RFCs is biased by less than 25%
Long Range Prediction Goal:
Provide long-lead guidance for water resource management

Assess accumulated flow error

Based on 71 days of NWM forecasts from WCOSS versus ~1000 USGS Gages II unregulated stations, May-June 2016

Preliminary Findings
- All regional median 30 day total volume inflow errors less than 3k ac-ft, much less than mean inflow
- Regional breakout by RFC reveals an underlying dry bias
Ongoing Work:
Assessment of how much errors in QPF contribute to errors in streamflow?

Sample type of plot that will be used to examine key relationship between precipitation forcing and NWM streamflow forecast accuracy
# Rwrphydro: R package for WRF-Hydro Model Evaluation

[https://github.com/mccreigh/rwrphydro](https://github.com/mccreigh/rwrphydro)

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National Water Model Evaluation: Evapotranspiration

Streamflow Bias by Ecoregion

Modeled ET Errors by Ecoregion
Validation against EC-MOD (Xiao 2011)

Modeled ET Errors at Ameriflux Stations
SPINUP16YR_No_Routing_v1.1, NA to NA

Mean Daily Absolute Error (mm)
-3
-2
-1
0
1
2
3

Bias (%)
< -60%
-60 to -20%
-20 to 0%
0 to 20%
> 20%

Bias (%)
< -60%
-60 to -20%
-20 to 0%
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IOC Model Evaluation: Evapotranspiration

HydroInspector(Gadget!): National Water Model

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- National Water Center Snow Data Assimilation System (SNODAS)
- Snow Telemetry Network (SNOTEL)
- NASA Airborne Snow Observatory (ASO)
NWM Calibration Procedure:

- Regional prioritization (~15)
  - Regions of large coherent biases
  - Other critical regions as identified via NOAT teams
- Parameter Sensitivity Analysis
- Calibration runs:
  - Multiple criteria with emphasis on bias reduction (NSE, RMSE, % bias, correlation, KGE)
  - Automated Rwrhydro-NWM workflow
  - Manual parameter adjustments as necessary
- Regionalize parameter sets based on Ohmerik’s ‘Ecoregions’
- Re-validate full CONUS with 5-yr runs
NWM Improvements: Southeast Region

Priorities:

- Increase soil water storage capacity to mimic wetland-type systems
- Include spatially distributed, dynamic vegetation parameters (e.g., LAI)
- Improve representation of groundwater exchanges (e.g., fully coupled deep groundwater layer)
Priority Opportunities and Needs

• Evaluation of all meteorological forcings that are hydrologically relevant
  • VIP – HRRR related precipitation biases

• Improved depiction of water management influences

• ‘Local’ knowledge and expertise in forecast error diagnoses (lead to better calibration, parameter estimation, process representation)

• Forecast post-processing
The R2O-O2R Paradigm

- Comprehensive model analysis tools to identify sources of error
- Prioritize upgrade and development priorities
- Engage community to develop prototype solutions
- Assess national scalability, develop implementation strategy
Thanks!

Any Questions:

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- adugger@ucar.edu
- jamesmcc@ucar.edu
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National Water Model:

- [http://water.noaa.gov/about/nwm](http://water.noaa.gov/about/nwm)

WRF-Hydro:

- [https://www.ral.ucar.edu/projects/wrf_hydro](https://www.ral.ucar.edu/projects/wrf_hydro)

Rwrfhydro Evaluation Tools:

- [https://github.com/mccreigh/rwrfhydro](https://github.com/mccreigh/rwrfhydro)