Overview of the WRF-Hydro Modeling System


National Center for Atmospheric Research
Motivation: An Array of Water Issues

Spatial Scales:
- Watershed
- Global

Temporal Scales:
- Design
- Climate Adaptation

“Hydrology of Now”
Overarching WRF-Hydro System Objectives

A community-based, supported coupling architecture designed to provide:

1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as precipitation, soil moisture, snowpack, groundwater, streamflow, inundation

2. ‘Accurate’ and ‘reliable’ streamflow prediction across scales (from 0-order headwater catchments to continental river basins & minutes to seasons)

3. A robust framework for land-atmosphere coupling studies
Water Cycle Modeling and Prediction within the WRF-Hydro System

Colorado Flood of 11-15 Sept. 2013

Accumulated Precipitation (shaded colors)
100m gridded streamflow (points)
1. Forecasts of water everywhere all the time

Current efforts are demonstrating the feasibility of Operational Quantitative Streamflow Forecasting (QSF):

- NSSL-FLASH, WRF-Hydro, LISFLOOD (UK), RAPID
- Spatial resolutions > 100m better
- Allows cycling from QPE and forecasting from QPN/QPF
- Emphasis on 0-6 hr gap
1. Forecasts of water everywhere all the time

The NOAA National Water Model

Snow Water Equivalent (SNEQV): Oct. 23, 2018

Total Column % Saturation ("SOILSAT"): Oct. 23, 2018
1. Forecasts of water everywhere all the time

The NOAA National Water Model
Variability in surface fluxes are strongly coupled to convective initiation and cloud formation. Complex, non-linear feedback require coupled system representation.
Including the control effects of and impacts on infrastructure:

- Dams and reservoirs (passive and actively managed)
- Overbank storage and attenuation
- Diversion structures, headgates
- Levees, dikes
- Failures of infrastructure (exceeding design capacity)

* Needs Infrastructure & Operations Data Standards
Quantify analysis and forecast uncertainty to provide meaningful risk guidance

Provide forecasters and decision makers with probabilities of:

• Locations and time of rapid river stage increase
• Duration of high waters and inundation

Requires maximizing the utility of High Performance Computing (HPC)
5. Hydro-system dynamics

Improving representation of landscape dynamics essential to flood risks:

• Geomorphological:
  – Bank stability
  – Sediment transport/deposition
  – Debris flows

• Land cover change due fire, urbanization, ag/silviculture

* Needs: improved channel, soils and land cover geospatial data
WRF-Hydro System Specifics
WRF-Hydro operates in two major modes: coupled or uncoupled to an atmospheric model.

- **Uncoupled mode** critical for spinup, data assimilation, and model calibration.
- **Coupled mode** critical for land-atmosphere coupling research and long-term predictions.

Model forcing and feedback components mediated by WRF-Hydro:

- Forcings: T, Press, Precip., wind, radiation, humidity, BGC-scalars
- Feedbacks: Sensible, latent, momentum, radiation, BGC-scalars
WRF-Hydro Modular Calling Structure

- Standalone Mode (uncoupled): Gridded Forcing Data
- Coupled Mode: Nowcast, Weather & Climate Models
- Alternate Hydrological/Land Model Drivers (e.g. LIS, CESM, CSDMS)

Optional Data Assimilation: DART

WRF-Hydro Driver/Coupler

- Optional Spatial Transformation
- Land Surface Model (if necessary)
- Subsurface Flow Routing
- Optional Spatial Transformation
- Overland Flow Routing
- Optional Spatial Transformation
- Baseflow Model
- Optional Spatial Transformation
- Channel & Reservoir Routing w/ Water Management, Nudging
Completed:
• Stand-alone, “Un-coupled” (1-d Noah & NoahMP land model driver)
• Coupled with the Weather Research and Forecasting Model (WRF-ARW)
• NOAA/NEMS (NOAA Environmental Modeling System, NUOPC)
• Coupled with LIS (WRF-Hydro v5.0, LISv7.2)
• Coupled into DART

In Progress:
• Coupling with PARFLOW integrated surface water / groundwater model (Col. School of Mines)
Modularized Fortran
Coupling options are specified at compilation and WRF-Hydro is compiled as a new library in WRF when run in coupled mode
Physics options are switch-activated though a namelist/configuration file
Options to output sub-grid state and flux fields to standards-based netcdf point and grid files
Fully-parallelized to HPC systems (e.g. NCAR supercomputer) and “good” scaling performance
Ported to Intel, IBM and MacOS systems and a variety of compilers (pg, gfort, ifort)
WRF-Hydro Physics Components Overview
Land surface parameterizations:

Table 24.1  Requirements in a Soil-Vegetation-Atmosphere Transfer (SVAT) scheme: (A) Basic variables that must be calculated at each model time step by a SVAT if it is used in a meteorological model; (B) Additional required calculations to allow representation of the hydrological impacts of climate; (C) Additional required calculations to allow representation of changes in CO₂ (and perhaps other trace gases) in the atmosphere.

A. Basic requirements in meteorological models

1. Momentum absorbed from the atmosphere by the land surface – requires the effective area-average aerodynamic roughness length.
2. Proportion of incoming solar radiation captured by the land surface – requires the effective area-average, wavelength average solar reflection coefficient or albedo.
3. Outgoing longwave radiation (calculated from area-average land surface temperature) – requires the effective area-average, wavelength average emissivity of the land surface.
4. Effective area-average surface temperature of the soil-vegetation-atmosphere interface - required to calculate longwave emission and perhaps energy storage terms.
5. Area-average fraction of surface energy leaving as latent heat (with the remainder leaving as sensible heat) - to calculate this other variables such as soil moisture and/or measures of vegetation status are often required, these either being prescribed or calculated as state variables in the model.
6. Area-average of energy entering or leaving storage in the soil-vegetation-atmosphere interface (required to calculate the instantaneous energy balance).

B. Required in hydro-meteorological models to better estimate area-average latent heat and to describe the hydrological impacts of weather and climate

7. Area-average partitioning of surface water into evapotranspiration, soil moisture, surface runoff, interflow, and baseflow.

C. Required in meteorological models to describe indirect effect of land surfaces on climate through their contribution to changes in atmospheric composition

8. Area-average exchange of carbon dioxide (and possibly other trace gases).
- Linking the column structure of land surface models with the ‘distributed’ structure of hydrological models in a flexible, HPC architecture....
Terrain features affecting moisture availability (scales ~1km)

Routing processes: the redistribution of terrestrial water across sloping terrain
- Overland lateral flow (dominates in semi-arid climates)
- Subsurface lateral flow (dominates in moist/temperate climates)
- Shallow subsurface waters (in topographically convergent zones)

Channel processes

Built environment/infrastructure

Water management

Other land surface controls:
- Terrain-controlled variations on insolation (slope-aspect-shading)
- Soil-bedrock interactions

Courtesy the COMET Program
Goal...
WRF-Hydro V5.0 Physics Components

Runoff and Routing Physics:

Overland Flow

Lateral Subsurface Flow

Simplified Baseflow Parameterization

Channel Hydraulics

Simple Water Management

Adapted from: Julian et al, 1995 – CASC2D, GSSHA
## WRF-Hydro Options

### Current NWM Configuration

<table>
<thead>
<tr>
<th>Column Land Surface Model</th>
<th>3 up-to-date column land models: Noah, NoahMP (w/ built-in multi-physics options), Sac-HTET</th>
<th>NoahMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overland Flow Module</td>
<td>3 surface routing schemes: diffusive wave, kinematic wave, direct basin aggregation</td>
<td>Diffusive wave</td>
</tr>
<tr>
<td>Lateral Subsurface Flow Module</td>
<td>2 subsurface routing scheme: Boussinesq shallow saturated flow, 2d aquifer model</td>
<td>Boussinesq shallow saturated flow</td>
</tr>
<tr>
<td>Conceptual Baseflow Parameterizations</td>
<td>2 groundwater schemes: direct aggregation storage-release: pass-through or exponential model</td>
<td>Exponential model</td>
</tr>
<tr>
<td>Channel Routing/Hydraulics</td>
<td>5 channel flow schemes: diffusive wave, kinematic wave, RAPID, custom-network Muskingum or Muskingum-Cunge</td>
<td>Custom-network (NHDPlus) Muskingum-Cunge model</td>
</tr>
<tr>
<td>Lake/Reservoir Management</td>
<td>1 lake routing scheme: level-pool management</td>
<td>Level-pool management</td>
</tr>
</tbody>
</table>
Current Land Surface Models:

- Column physics & land-atmosphere exchange

WRF-Hydro V5.0 Physics Components

Noah LSM & Noah-MP
NoahMP Column Physics:

Noah-MP contains several options for land surface processes:

1. Dynamic vegetation/vegetation coverage (4 options)
2. Canopy stomatal resistance (2 options)
3. Canopy radiation geometry (3 options)
4. Soil moisture factor for stomatal resistance (3 options)
5. Runoff and groundwater (4 options)
6. Surface layer exchange coefficients (4 options)
7. Supercooled soil liquid water/ice fraction (2 options)
8. Frozen soil permeability options (2 options)
9. Snow surface albedo (2 options)
10. Rain/snow partitioning (3 options)
11. Lower soil boundary condition (2 options)
12. Snow/soil diffusion solution (2 options)

Total of ~50,000 permutations can be used as multi-physics ensemble members

Noah/NoahMP development lead by M. Barlage and F. Chen, NCAR
WRF-Hydro V5.0 Physics Components

• Multi-scale aggregation/disaggregation:

![100m Terrain](image1)

![1 km Terrain](image2)

Current ‘Regridding’

Terrain slope (0-45 deg)

Implementing ESMF Regridders
WRF-Hydro V5.0 Physics Components

- Multi-scale aggregation/disaggregation:
Terrain Routing
Surface 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

- 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 in v5

- 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

- **Critical initialization value:** water table depth

Adapted from:
Wigmosta et. al, 1994
Conceptual groundwater baseflow “bucket” model:

- Simple pass-through or 2-parameter exponential model
- Bucket discharge gets distributed to channel network
Subsurface Routing in v5

- 2D groundwater model
- Coupled to bottom of LSM soil column through Darcy-flux parameterization
- Independent hydraulic characteristics vs. soil column
- Full coupling to gridded channel model through assumed channel depth and channel head
- Detailed representation of wetlands

Surface ponded water from coupled groundwater in WRF-Hydro
B. Fersch, KIT, Germany
Channel Routing
Channel routing: Gridded vs. Reach-based

- **Solution Methods:**
  - Gridded: 1-d diffusive wave: fully-unsteady, explicit, finite-difference
  - Reach: Muskingum, Muskingum-Cunge (*much faster*)

- **Parameters:**
  - A priori function of Strahler order
  - Trapezoidal channel (bottom width, side slope)
Optional conceptual ‘Bucket’ models:

- Used for continuous (vs. event) prediction
- Simple pass-through or 2-parameter exponential model
- Bucket discharge gets distributed to channel network
Lakes & Reservoirs
WRF-Hydro V5.0 Physics Components : Lake/Reservoir Representation

- Defined in GIS Pre-processing, integrated with channel hydrograph
- Specified spillway characteristics (length, height)

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

- Development:
  - Basic thermodynamics (CLM/WRF lake model)
  - Full lake accounting
    - Evaporation
    - Ice formation
    - Inflows/outflows
    - Simple management
  - Coupling to FVCOM (GLERL)
WRF-Hydro Model Architecture

- Modes of operation: 1-way vs. 2-way
- Model forcing and feedback components:
  - Forcings: T, Press, Precip., wind, radiation, humidity, BGC-scalars
  - Feedbacks: Sensible, latent, momentum, radiation, BGC-scalars
Model Parallelization
Data Grids:

• Three Data Grids
  Land Grids: (ix,jx), (ix,jx, n_soil_layer)
  Land Routing: (ixrt,jxrt), (ixrt,jxrt,n_soil_layer)
  Channel Routing: (n_nodes), (n_lakes)

• Parallel Scheme
  • Two dimensional domain decomposition
  • Distributed system only
One CPU: Land grid, land routing grid cell, and channel routing nodes.
Distributed memory communications land grid:

Stand alone columns require no memory communication between neighbor processors
Lateral routing DOES require memory communication between neighbor processors
Lateral channel routing DOES require memory communication between neighbor processors, although the arrays are reduced to the sparse matrix of the channel elements
The WRF-Hydro Workflow
WRF-Hydro Base Configuration

Noah/NoahMP LSM

MODEL PHYSICS

Terrain Routing Modules

Channel & Reservoir Routing Modules
Full WRF-Hydro Ecosystem

NWM Forcing Engine

Geospatial Pre-Processing

Hydro-DART Data Assimilation

Noah/NoahMP LSM

Terrain Routing Modules

MODEL PHYSICS

NHDPlus Catchment Aggregation

Channel & Reservoir Routing Modules

Rwrfhydro Model Evaluation & Calibration

HydroInspector Web-Mapping Service
Collect geospatial terrain and hydrographic data

Prepare:
- Land model grids (WPS)
- Routing Grids/Networks (ArcGIS)

Collect & Prepare Meteorological Forcings: (uncoupled runs)

Conduct uncoupled model runs:
- Physics selection
- Calibration
- Assimilation &/or spinup

Execute uncoupled forecast cycles: Nowcasts, NWP QPF

Prepare Atmospheric Model: (coupled runs)

Execute coupled-model forecast cycles

Create output forecast & evaluation products
WRF-Hydro input and parameter files organized by model physics component. See the Key for files specific to a certain land model or channel configuration.
WRF-Hydro Workflow - custom geographical inputs

1. Define the Domain:
   WRF-ARW/WPS: geogrid.exe
   inputs: namelist.wps, geographic data
   Outputs: GEOGRID file
   (defines the domain and grid)

2. Define Initial Conditions:
   create_Wrfinput.R script
   inputs: GEOGRID file
   Outputs: wrfinput file
   (initial conditions for a cold start and other default model parameters)

3. Create Hydrologic Routing Inputs:
   WRF-Hydro GIS Pre-Processing Tool
   Inputs: GEOGRID file, station points, lakes
   Outputs: Full domain file, geospatial metadata file, Optional routing files

4. Prepare Meteorological Forcing Data:
   ESMF regridding scripts
   inputs: raw met. data, GEOGRID file, (regridded to match the GEOGRID domain from step 1)
   Outputs: LDASIN (and optional PRECIP) files

5. Run Model Simulations:
   wrf_hydro.exe
   Inputs: GEOGRID file, fulldom_hires.nc, namelist.h0000
   hydro.namelist, wrfinput file, Optional routing files, LDASIN & optional PRECIP files,
   Outputs: model outputs

6. Evaluate Model Output:
   WrfHydro
   Inputs: model outputs, observations
   Outputs: analyses, verifications, visualizations, etc.
Model System Components

- **GIS Pre-Processor** – Physiographic data processing
- **ESMF Regridding Scripts** – Met. data pre-processing
- **Core WRF-Hydro Model** – Model physics
- **Rwrfhydro** – Analysis, verification, visualization
- **PyWrfHydroCalib** – Model calibration toolkit
WRF-Hydro Setup and Parameterization: Python Pre-Processing Toolkit

- Python-based scripts
- ESRI ArcGIS geospatial processing functions
  - Support of multiple terrain datasets
    - NHDPlus, Hydrosheds, EuroDEM

Outputs: topography, flowdirection, watersheds, gridded channels, river reaches, lakes, various parameters

K. Sampson - developer
https://github.com/NCAR/wrf_hydro_arcgis_preprocessor
NEW!!! Python-based code...

- NLDAS, NARR analyses
- QPE products: MPE, StgIV, NCDC-served, dual-pol, Q3/MRMS, gauge analyses, CMOPRH, TRMM, GPM
- NOAA QPF products: GFS, NAM, RAP, HRRR, ExREF
- Nowcast (NCAR Trident/TITAN)
- NOHRSC SNODAS
- ESMF regridding tools

Regridded MPE precipitation during the 2013 Colorado Floods
Unidata IDV display
Blended MRMS-HRRR Precipitation

Seasonally-varying MRMS RQI

HRRR-RAP incoming longwave radiation

HRRR-RAP 2m Air Temperature

GFS – derived incoming shortwave radiation
Current capabilities

• Ensemble DA:
  • Offline WRF Hydro + DART = “HydroDART”

• Ensemble generation:
  • Initial state & parameter perturbation, ensemble runs

Future capabilities

• Variational DA and/or nudging:
  • Faster & computationally cheaper for large-scale applications.
  • Variational DA not rank-deficient

• Other kinds of DA (hybrid, MLEF, …)

• Bias-aware filtering / Two-stage bias estimation (Friedland, 1969; Dee and de Silva, 1998; De Lannoy et al., 2007)
Rwrfhydro: R package for hydrological model evaluation

**Observations Ingested for Model Evaluation in Rwrfhydro:**

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Dataset</th>
<th>Data type/format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate: precipitation, temperature, humidity, pressure, wind speed</td>
<td>GHCN</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>USCRN</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>HADS</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>SNOTEL</td>
<td>point obs</td>
</tr>
<tr>
<td>Snow: SWE, fSCA, albedo</td>
<td>SNOTEL</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>SNODAS</td>
<td>raster</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td>raster</td>
</tr>
<tr>
<td>Soil Moisture: volumetric soil moisture by layer</td>
<td>SCAN</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>USCRN</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>ISMN</td>
<td>point obs</td>
</tr>
<tr>
<td>Energy: ET, skin temperature, albedo</td>
<td>Ameriflux</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td>raster</td>
</tr>
<tr>
<td>Streamflow: flowrate, celerity</td>
<td>USGS</td>
<td>point obs</td>
</tr>
<tr>
<td></td>
<td>CO &amp; CA DWR</td>
<td>point obs</td>
</tr>
</tbody>
</table>

https://github.com/NCAR/rwrfhydro
WRF-Hydro Software Ecosystem

- Ecosystem overview: [https://github.com/NCAR/wrfHydro](https://github.com/NCAR/wrfHydro)
- Model: [https://github.com/NCAR/wrf_hydro_nwm_public](https://github.com/NCAR/wrf_hydro_nwm_public)
  - Public, community model, with version control system
  - Contributing guidelines, conventions, license, code of conduct
  - Python-based (pytest) testing framework (Python API)
- Python API: [https://github.com/NCAR/wrf_hydro_py](https://github.com/NCAR/wrf_hydro_py)
- Docker containers: [https://github.com/NCAR/wrf_hydro_docker](https://github.com/NCAR/wrf_hydro_docker)
  - Standard portable environments for working with the model
- Continuous Integration with Travis on Github (Docker + Python)
- “Discontinuous integration” at scale (cheyenne)
  - Large jobs, compilers with licenses
- ARC GIS preprocessing toolbox: [https://github.com/NCAR/wrf_hydro_arcgis_preprocessor](https://github.com/NCAR/wrf_hydro_arcgis_preprocessor)
- Analysis tool box: [https://github.com/NCAR/rwrfhydro](https://github.com/NCAR/rwrfhydro)
- Training: [https://github.com/NCAR/wrf_hydro_training](https://github.com/NCAR/wrf_hydro_training)
Community resources:

- Improved WRF-Hydro website & internet presence
- Helpdesk support
- New & increased volume of documentation, user guides, FAQs
- New test cases (standalone & coupled)
- Github repository
- Containerization of pre-processing tools & model run environment --> lowers barrier of entry

Online Training Suite:

- YouTube video demo (w/ Spanish translation)
- Self-contained training modules using Docker & Jupyter Notebooks

New lines of Communication & Support:

- Email listserv
- Online contact form + helpdesk ticketing system
- Online user forum - (users helping users)
- Twitter @WRFHydro
- Community spotlight
  - Users, research, & contributions to WRF-Hydro Community
WRF-Hydro Applications Around the Globe

Operational Streamflow Forecasting
- U.S. National Weather Service National Water Model (NOAA/NWS, National Water Center, USGS, CUAHSI)
- Israel National Forecasting System (Israeli Hydrological Service)
- NCAR-STEP Hydrometeorological Prediction (NCAR)
- Italy reservoir inflow forecasting (Univ. of Calabria)
- Romania National Forecasting System (Baron)

Streamflow Prediction Research
- Flash flooding in Black Sea region of Turkey (Univ. of Ankara)
- Runoff production mechanisms in the North American Monsoon (Ariz State Univ.)
- Streamflow processes in West Africa (Karlsruhe Inst. Tech.)

Coupled Land-Atmosphere Processes
- Diagnosing land-atmosphere coupling behavior in mountain-front regions of the U.S. and Mexico (Arizona State Univ., Univ. of Arizona)
- Quantifying the impacts of winter orographic cloud seeding on water resources (Wyoming Board on Water Resources)
- Predicting weather and flooding in the Philippines, Luzon Region (USAID, PAGASA, AECOM)
- RELAMPAGO in Argentina (Univ. of Illinois Urbana-Champaign, NCAR)

Diagnosing Climate Change Impacts on Water Resources
- Himalayan Mountain Front (Bierknes Inst.)
- Colorado Headwaters (Univ. of Colorado)
- Bureau of Reclamation Dam Safety Group (USBR, NOAA/CIRES)
- Lake Tanganyika, Malawi, Water Supply (World Bank)
- Climate change impacts on water resources in Patagonia, Chile (Univ. of La Frontera)

Coupling WRF-Hydro with Coastal Process Models
- Italy-Adriatic sea interactions (Univ. of Bologna)
- Lower Mississippi River Valley (Louisiana State University)
- Integrated hydrological modeling system for high-resolution coastal applications (U.S. Navy, NOAA, NASA)

Diagnosing the Impacts of Disturbed Landscapes on Hydrologic Predictions
- Western U.S. Fires (USGS)
- West African Monsoon (Karlsruhe Inst. Tech)
- S. America Parana River (Univ. of Arizona)
- Texas Dust Emissions (Texas A&M Univ.)
- Landslide Hazard Modeling (USGS)

Hydrologic Data Assimilation:
- MODIS snow remote sensing assimilation for water supply prediction in the Western U.S. (Univ. of Colorado, Univ. of California Santa Barbara, NSIDC, NCAR)
- WRF-Hydro/DART application in La Sierra River basins in southeast Mexico (Autonomous National University of Mexico)