WRF-Hydro Modeling System: Physics Components


National Center for Atmospheric Research
Basic Concepts:

- Linking the column structure of land surface models with the ‘distributed’ structure of hydrological models in a flexible, HPC architecture....
• Atmospheric coupling perspective and serving the WRF research and forecasting and CESM communities

• Oriented towards existing NCAR-supported community models, but expanding:
  – Not fully genericized coupling which has pros/cons associated...
  – Also aimed at cluster & HPC architectures
WRF-Hydro V5.0 Physics Components

Goal...
Runoff and Routing Physics:

**Overland Flow**

- Infiltration excess available for hydraulic routing

**Lateral Subsurface Flow**

- Surface Exfiltration from Saturated Soil Columns
- Lateral Flow from Saturated Soil Layers

**Simplified Baseflow Parameterization**

- Adaptive from Julian et al, 1995 – CASC2D, GSSHA

**Channel Hydraulics**

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

- Column physics & land-atmosphere exchange

- Land surface models are used to partition incoming surface energy and water into outgoing/internal fluxes and internal storage
- Land surface models are evolving to better represent reality and to expand user bases
- Evolving land surface model structure is leading to new challenges, e.g., parameters, parameters!
- Knowledge of both model structure and parameter assumptions is essential to properly use an LSM

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
Land surface models, as an upper boundary of a soil hydrology model, take:

- Precipitation and partition into fluxes (evapotranspiration, surface/underground runoff) and storage (soil moisture and snowpack)
- Solar and atmospheric energy and partition in fluxes (ET, sensible heat, ground/snow heat) and storage (snow/soil heat content)

Models are generally 1D.
Conceptual Land Surface Processes

- Precipitation
- Condensation
- Snowmelt
- Surface Runoff
- Transpiration
- Canopy Water Evaporation
- Direct Soil Evaporation
- Evaporation from Open Water
- Soil Heat Flux
- Internal Soil Moisture Flux
- Interflow
- Soil Moisture Flux
- Internal Soil Heat Flux
- Gravitational Flow

\[
\Delta Z = 10 \text{ cm} \\
\Delta Z = 30 \text{ cm} \\
\Delta Z = 60 \text{ cm} \\
\Delta Z = 100 \text{ cm}
\]
The community Noah land surface model with multiparameterization options (Noah-MP):

1. Model description and evaluation with local-scale measurements

Guo-Yue Niu,1,2 Zong-Liang Yang,1 Kenneth E. Mitchell,3 Fei Chen,4 Michael B. Ek,3 Michael Barlage,4 Anil Kumar,5 Kevin Manning,4 Dev Niyogi,6 Enrique Rosero,1,7 Mukul Tewari,4 and Youlong Xia3

Received 4 October 2010; revised 3 February 2011; accepted 27 March 2011; published 24 June 2011.

The community Noah land surface model with multiparameterization options (Noah-MP):

2. Evaluation over global river basins

Zong-Liang Yang,1 Guo-Yue Niu,1,2 Kenneth E. Mitchell,3 Fei Chen,4 Michael B. Ek,3 Michael Barlage,4 Laurent Longuevergne,5 Kevin Manning,4 Dev Niyogi,6 Mukul Tewari,4 and Youlong Xia3

Received 4 October 2010; revised 4 February 2011; accepted 25 March 2011; published 24 June 2011.
Noah-MP Calling Structure: Modularity at the Process Level

Noah-MP

ENERGY

- Canopy resistance
  - Jarvis
  - Ball-Berry

- Radiative Transfer
  - Two-stream
  - Geometric shade

WATER

- Runoff Options
  - Free Drainage
  - 2D Aquifer

CARBON

- Vegetation Growth
  - Prescribed phen.
  - Dynamic Veg.
Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
- Dynamic vegetation
- Vegetation canopy resistance
- Multi-layer snowpack
- Snowpack liquid water retention
- Simple groundwater options
- Snow albedo treatment
- New frozen soil scheme
- New snow cover
\[ \text{SW}_{\text{dn}} - \text{SW}_{\text{up}} + \text{LW}_{\text{dn}} - \text{LW}_{\text{up}} (T_{\text{sfc}}) = \text{SH}(T_{\text{sfc}}) + \text{LH}(T_{\text{sfc}}) + G(T_{\text{sfc}}) \]

- \( \text{SW}_{\text{dn}}, \text{LW}_{\text{dn}} \): input shortwave and longwave radiation (external to LSM)
- \( \text{SW}_{\text{up}} \): reflected shortwave (albedo)
- \( \text{LW}_{\text{up}} \): upward thermal radiation
- \( \text{SH} \): sensible heat flux
- \( \text{LH} \): latent heat flux (soil/canopy evaporation, transpiration)
- \( G \): heat flux into the soil
Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes:

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
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Soil Moisture

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D \frac{\partial \theta}{\partial z} \right) + \frac{\partial K}{\partial z} + F_\theta \]

- Richards Equation for soil water movement
- $D, K$ are functions of soil texture and soil moisture
- $F_\theta$ represents sources (rainfall) and sinks (evaporation)

Soil/Snow Temperature

\[ C(\theta) \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K_t(\theta) \frac{\partial T}{\partial z} \right) \]

- $C, K_t$ are functions of soil texture and soil moisture
- Soil temperature information used to compute ground heat flux
Noah-MP has a separate canopy and uses a two-stream radiative transfer treatment through the canopy.

**Canopy parameters:**
- Canopy top and bottom
- Crown radius, vertical and horizontal
- Vegetation element density, i.e., trees/grass leaves per unit area
- Leaf and stem area per unit area
- Leaf orientation
- Leaf reflectance and transmittance for direct/diffuse and visible/NIR radiation

**Multiple options for spatial distribution**
- Full grid coverage
- Vegetation cover equals prescribed fractional vegetation
- Random distribution with slant shading
• Land-cover/vegetation classification
  – Many sources, generally satellite-based and categorically broad

• Soil texture class
  – Also general with large consolidations

• Many secondary parameters that can be specified as function of the above
Datasets: NLCD Land Cover
MPTABLE.TBL contains a lookup table for vegetation classes

Limitations:

All pixels with the same vegetation have the same parameters

Modifying parameters affects all vegetation of the same type

<table>
<thead>
<tr>
<th>Parameters: Land Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>maize_1</td>
</tr>
<tr>
<td>maize_2</td>
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<tr>
<td>maize_3</td>
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<tr>
<td>maize_4</td>
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<tr>
<td>maize_5</td>
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<tr>
<td>maize_6</td>
</tr>
<tr>
<td>maize_7</td>
</tr>
<tr>
<td>maize_8</td>
</tr>
<tr>
<td>maize_9</td>
</tr>
</tbody>
</table>
• Vegetation varying in time and space
• Comparison of MODIS LAI to default table-based LAI
SOILPARM.TBL contains a look-up table for soil texture classes

Limitations:

All pixels with the same soil type have the same parameters

Modifying parameters affects all soil of the same type
Datasets: Soil Composition
Some capabilities exist within Noah-MP to read spatially-dependent soil and vegetation properties

 Allows users who have local information to access it in the model

 Soil properties: \( b \), \( dksat \), \( dwsat \), \( psisat \), \( smcdry \), \( smcmax \), \( smcref \), \( smcwlt \), \( slope \), \( refdk \), \( refkdt \), \( rsurfexp \), quartz

 Vegetation properties: \( cwpvt \), \( hvt \), \( mp \), \( vcmx25 \), \( mfsno \)
WRF-Hydro V5.0 Physics Components

- Multi-scale aggregation/disaggregation:

100m Terrain

1 km Terrain

Current ‘Regridding’

Implementing ESMF Regridders

Terrain slope (0-45 deg)
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

Infiltration excess available for hydraulic routing
<table>
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<tr>
<td><strong>Runtime Settings</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OVRTSWCRT</td>
<td>Overland routing physics switch (on/off)</td>
<td>hydro.namelist</td>
<td>Landscape/event, compute resources (computationally intensive)</td>
</tr>
<tr>
<td>DTRT_TER</td>
<td>Overland routing timestep</td>
<td>hydro.namelist</td>
<td>Based on grid size, landscape/event</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOPOGRAPHY</td>
<td>Land surface elevation; routing based on elevation+head gradient</td>
<td>Routing grid (Fulldom)</td>
<td>Various sources</td>
</tr>
<tr>
<td>OV_ROUGH2D</td>
<td>Overland roughness (Manning’s n for land)</td>
<td>LSM grid (hydro2dtbl)</td>
<td>Estimated based on land cover type</td>
</tr>
<tr>
<td>OVROUGHRTFAC</td>
<td>Multiplier on overland roughness</td>
<td>Routing grid (Fulldom)</td>
<td>Calibrated</td>
</tr>
<tr>
<td>RETDEPRTFAC</td>
<td>Multiplier on maximum retention depth on surface before overland flow processes are initiated</td>
<td>Routing grid (Fulldom)</td>
<td>Calibrated (internally scaled based on topographic slope)</td>
</tr>
</tbody>
</table>
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
# Subsurface Routing: Key Settings and Parameters

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Runtime Settings</strong></td>
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<td></td>
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<tr>
<td>SUBRTSWCRT</td>
<td>Subsurface routing physics switch (on/off)</td>
<td>hydro.namelist</td>
<td>Landscape/event</td>
</tr>
<tr>
<td>NOAH_TIMESTEP</td>
<td>LSM timestep</td>
<td>namelist.hrldas</td>
<td>Landscape/event</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOPOGRAPHY</td>
<td>Land surface elevation; routing based on elevation+head gradient</td>
<td>Routing grid (Fulldom)</td>
<td>Various sources</td>
</tr>
<tr>
<td>LKSAT</td>
<td>Lateral saturated hydraulic conductivity</td>
<td>LSM grid (hydro2dtbl)</td>
<td>Estimated based on soil texture class</td>
</tr>
<tr>
<td>LKSATFAC</td>
<td>Multiplier on lateral conductivity</td>
<td>Routing grid (Fulldom)</td>
<td>Calibrated</td>
</tr>
<tr>
<td>SMCMAX1</td>
<td>Soil porosity</td>
<td>LSM grid (hydro2dtbl)</td>
<td>Estimated based on soil texture class; calibrated</td>
</tr>
<tr>
<td>SMCREF1</td>
<td>Soil field capacity</td>
<td>LSM grid (hydro2dtbl)</td>
<td>Estimated based on soil texture class; calibrated</td>
</tr>
</tbody>
</table>
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
<table>
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<tbody>
<tr>
<td><strong>Runtime Settings</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWBASESWCRT</td>
<td>Baseflow bucket model switch (pass-through, exp, off)</td>
<td>hydro.namelist</td>
<td>Landscape/event</td>
</tr>
<tr>
<td>NOAH_TIMESTEP</td>
<td>LSM timestep</td>
<td>namelist.hrldas</td>
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</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWBASINS/spatialweights</td>
<td>Groundwater “basins”</td>
<td>LSM (GWBASINS) or routing grid (spatialweights)</td>
<td>Landscape</td>
</tr>
<tr>
<td>slope</td>
<td>“Openness” of bottom soil column boundary</td>
<td>LSM grid (soil_properties)</td>
<td>Calibrated</td>
</tr>
<tr>
<td>Coeff</td>
<td>Coefficient in exponential bucket equation</td>
<td>Bucket objects (GWBUCKPARAM)</td>
<td>Calibrated</td>
</tr>
<tr>
<td>Expon</td>
<td>Exponent in exponential bucket equation</td>
<td>Bucket objects (GWBUCKPARAM)</td>
<td>Estimated based on soil texture class; calibrated</td>
</tr>
<tr>
<td>Zmax</td>
<td>Maximum bucket depth</td>
<td>Bucket objects (GWBUCKPARAM)</td>
<td>Estimated based on soil texture class; calibrated</td>
</tr>
</tbody>
</table>
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
Optional lake/reservoir model:

- Level-pool routing (i.e. no lagging of wave or gradient in pool elevation)
- Inflows via channel and overland flow
- Discharge via orifice and spillway to channel network
- Parameters: lake and orifice elevations, max. pool elevation, spillway and orifice characteristics; specified via parameter table
- Active management can be added via an operations table
- Presently no seepage or evaporative loss functions
• Explicit, 1-D, variable time-stepping

• Diffusive wave in the model: simplified version of Continuity and Momentum St. Venant equations.

\[
\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial y}{\partial x} - g (S_o - S_f) = 0
\]

\[
Q = -\text{SIGN} \left( \frac{\partial Z}{\partial x} \right) K \sqrt{\left| \frac{\partial Z}{\partial x} \right|}
\]

where \( K \) is conveyance and \( Z \) is the water surface elevation. The \text{SIGN} function is 1 for \( \frac{\partial Z}{\partial x} > 0 \) and -1 for \( \frac{\partial Z}{\partial x} < 0 \).

• A numeric solution per channel grid pixel is obtained by discretizing the continuity eqn.

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}
\]

\[
A^{n+1} - A^n = \frac{\Delta t}{\Delta x} \left( Q_{i+1}^n - Q_{i-1}^n \right) + \Delta t q_{lat}^n
\]
Channel Routing Methods

- Set in hydro.namelist with the channel_option = 1, 2 or 3
- Channel_option 1 or 2 is “reach-based” or “vector” routing
- Channel_option = 3 is “gridded” or 1d diffusive wave
Storage routing method based on the continuity equation where,
\[ I - O = \frac{dS}{dt}, \quad I = \text{inflow}, \quad O = \text{outflow}, \quad S = \text{storage} \text{ and } t = \text{time} \]

General Muskingum equation:
\[ S = K[xI + (1 - x)O] \]

where \( K \) is a storage constant (also referred to as lag, travel time, etc.) and \( X \) is a weighting factor expressing relative importance of \( I \) & \( O \) to \( S \).

Simplified, implemented per reach in the channel network:
\[ O_2 = c_0I_2 + c_1I_1 + c_2O_1 \]

where \( c_0, c_1 \) and \( c_2 \) are functions of \( K, X \) and \( t \), whose sum is 1.
Similar to Muskingum, but with hydraulically derived parameters, $K$, the “storage constant” and $X$, “weighting factor”

$K = \frac{\Delta x}{c}$, where $\Delta x =$ reach length and $c$ is the celerity (wave speed)

$X = \frac{1}{2} \left( 1 - \frac{Q}{BcS_0\Delta x} \right)$, where $B =$ bottom width, $S_0$ is the slope

NWM channel routing uses this option for CONUS.

Benefits: faster computation and stable; Cons – flat, long reaches may not be appropriate.
• For gridded, `channel_option = 3`, we use the CHANPARM.TBL file to specify bottom width (Bw), side slope (z), roughness (n), HLINK.
• For reach-based, `channel_option = 1 or 2`, the Routelink.nc file specifies the parameters for every reach.
• Defaults for both: order based parameters.
### Channel Routing: Key Settings & Parameters

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</tr>
<tr>
<td>CHANRTSWCRT</td>
<td>Channel switch (on or off)</td>
<td>hydro.namelist</td>
<td>Landscape/event</td>
</tr>
<tr>
<td>channel_option</td>
<td>Routing method (Muskingum, Musk-Cunge, diffusive wave)</td>
<td>hydro.namelist</td>
<td>Landscape/event, compute resources (can be computationally intensive)</td>
</tr>
<tr>
<td>DTRT_CH</td>
<td>Channel routing timestep</td>
<td>hydro.namelist</td>
<td>Based on channel reach or grid size, landscape/event</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHANNELGRID</td>
<td>Channel/land mapping</td>
<td>Routing grid (Fulldom)</td>
<td>Landscape</td>
</tr>
<tr>
<td>BtmWidth, ChSlp</td>
<td>Channel geometry: bottom width and side slope</td>
<td>Reach (Route_Link) or CHANPARM lookup table</td>
<td>Linear model based on stream order or statistically derived</td>
</tr>
<tr>
<td>n</td>
<td>Channel roughness (Manning’s n)</td>
<td>Reach (Route_Link) or lookup table</td>
<td>Linear model based on stream order</td>
</tr>
<tr>
<td>So</td>
<td>Longitudinal downstream channel slope (reach only)</td>
<td>Reach (Route_Link)</td>
<td>Calculated from topography</td>
</tr>
<tr>
<td>MusK, MusX</td>
<td>Muskingum routing parameters (reach only)</td>
<td>Reach (Route_Link)</td>
<td>Estimated based on channel properties</td>
</tr>
</tbody>
</table>
Lakes & Reservoirs
- 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)
• Level-pool storage
• Multiple discharge modes

3 ‘passive’ discharge mechanisms:
• Orifice flow
• Spillway flow
• Direct Pass-through
• \( \Delta S = I - O \) (to include surface fluxes)
• Lakes are defined on the fine grid (in the Fulldom file ‘LAKEGRID’ var.)
• Channel pixels under lakes are erased
• Model identifies pixels as ‘inflow’ or ‘outflow’; only 1 outflow pixel allowed
• Level-pool performed on outflow pixel
Lakes are objects

**Why:** We can easily integrate with the flow network; vectorization speed.

**Implications:** Lakes outflow at a single point; the lake ‘module’ is run independently.
National Water Model Reservoirs

- V1.2: 1,507 NHDPlus water bodies
- Specified spillway characteristics (length, height)

- Default reservoir configuration: Level-pool scheme with parameterized discharge:
  - orifice
  - spillway

- Discharge Options Under Development:
  - Fixed/constant value
  - Operating Curves
  - Downstream stream gauge data assimilation
  - Management schedule

- Future:
  - Diversions
  - Reservoir evaporation
  - Irrigation
Implementation of 1-dimensional lake model

- Account for ice formation, rainfall, and evaporation fluxes over lakes.
- Adapt the WRF/CLM-LISSS lake scheme

Reservoir Operations

- Use observed lake outflows to assimilate flow/lake levels in managed reservoirs
- Machine learning to develop rule curves

Borrowed from Subin et al. 2012
Ongoing Work Related to Lake Development

Implementation of 1-dimensional lake model

Surface (0.1m)
2m
4m
6m
8m
10m

Vertical Temp Profile through Lake Winnebago
## Reservoir Level-Pool Routing: Key Settings & Parameters

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Runtime Settings</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>route_lake_f</td>
<td>Path to lake parameter file (if provided, lake model will be active)</td>
<td>hydro.namelist</td>
<td>Landscape/event</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAKEGRID or NHDWaterbodyComID</td>
<td>Location of lake object (gridded) ID of waterbody (NWM)</td>
<td>Routing grid (Fulldom) Route_Link</td>
<td>Landscape/event</td>
</tr>
<tr>
<td>LkArea, LkMxE</td>
<td>Lake geometry</td>
<td>LAKEPARAM.nc file</td>
<td>Area: derived from NHDPlus or provided; LkMxE derived from elevation grid</td>
</tr>
<tr>
<td>WeirC, WeirL, WeirE</td>
<td>Lake weir properties (constitutes “uncontrolled flow”)</td>
<td>LAKEPARAM.nc file</td>
<td>WeirE from elevation grid; coeff and length defaults</td>
</tr>
<tr>
<td>OrificeC, OrificeA, OrificeE</td>
<td>Lake orifice properties (constitutes “controlled flow”)</td>
<td>LAKEPARAM.nc file</td>
<td>OrificeE from elevation grid; coeff and area are defaults</td>
</tr>
</tbody>
</table>
Implementing lakes and reservoirs in WRF-Hydro

Visualization of lake impacts
WRF-Hydro Model Architecture

- Model physics components....
  - Multi-scale components....
    - Rectilinear regridding
    - ESMF regridding
    - Downscaling
• 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
<table>
<thead>
<tr>
<th>Type</th>
<th>When/Why To Use</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subsurface Routing</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SUBRTSWCRT</td>
<td>When local topography is important to flow processes or your fluxes/states of interest</td>
<td>Allows lateral water movement between cells, better representing convergence/divergence patterns (e.g., water converging into a valley) and residence times</td>
<td>More computationally expensive</td>
</tr>
<tr>
<td><strong>Overland Flow Routing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OVRTSWCRT</td>
<td>When fast surface flow processes are of interest/importance (e.g., flood forecasting vs. water supply forecasting)</td>
<td>Better represents local ponding and re-infiltration; required to capture land runoff directly to channels and lakes</td>
<td>More computationally expensive</td>
</tr>
<tr>
<td><strong>Channel Routing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHANRTSWCRT</td>
<td>When you want streamflow in the channel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muskingham-Reach</td>
<td>When you want an approximate solution as efficiently as possible (e.g., over a large domain or with limited compute resources)</td>
<td>Computationally cheap and fast</td>
<td>Limited to uniform fluxes/states per reach (not ideal if reaches are long); no backwater effects</td>
</tr>
<tr>
<td>channel_option = 1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Muskingham-Cunge-Reach</td>
<td>When you want an approximate solution as efficiently as possible (e.g., over a large domain or with limited compute resources)</td>
<td>Computationally cheap and fast; more “stable” in terms of propagating flow one-way down the channel</td>
<td>Limited to uniform fluxes/states per reach (not ideal if reaches are long); no backwater effects</td>
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<tr>
<td>channel_option = 2</td>
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</tr>
<tr>
<td>Diffusive Wave-Gridded</td>
<td>When you need a more precise/accurate local solution and have sufficient compute resources (e.g., small or high-resolution domains, conditions where hydraulic processes are important)</td>
<td>Captures backwater flow; provides higher spatial detail on channel flow (e.g., every channel grid cell); only option that allows (limited) water fluxes from land to lake</td>
<td>More computationally expensive, can be sensitive to parameters and internal time steps</td>
</tr>
<tr>
<td>channel_option = 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
WRF-Hydro: http://www.ral.ucar.edu/projects/wrf_hydro/