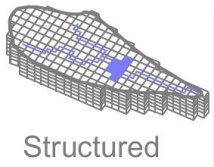
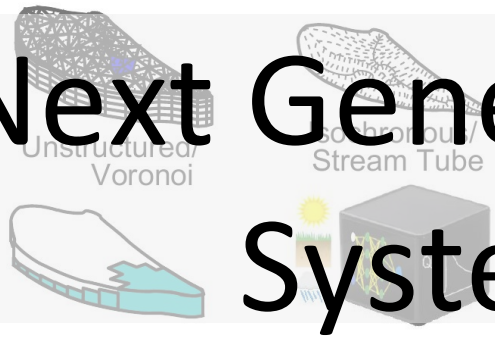
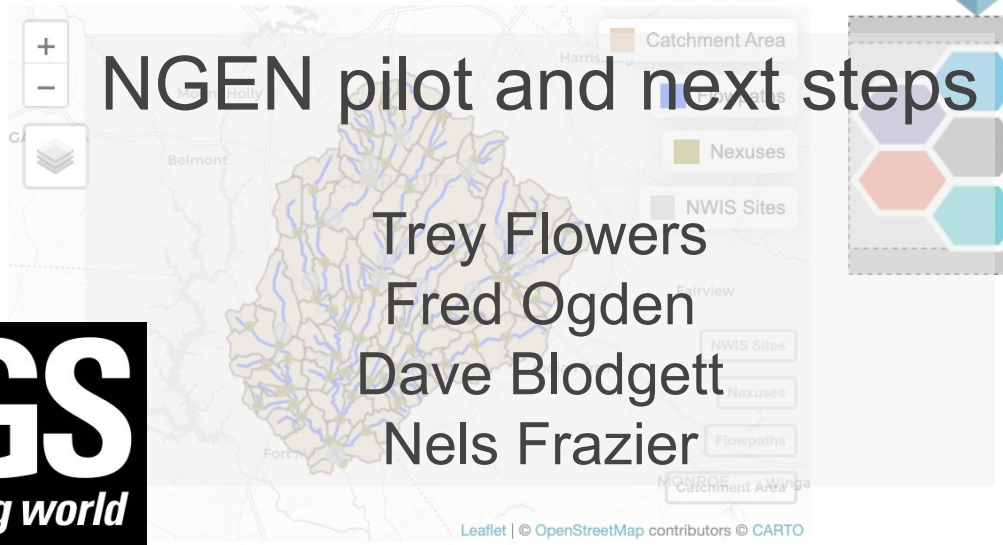




Next Generation Modeling System Webinar

NGEN pilot and next steps

Trey Flowers
Fred Ogden
Dave Blodgett
Nels Frazier



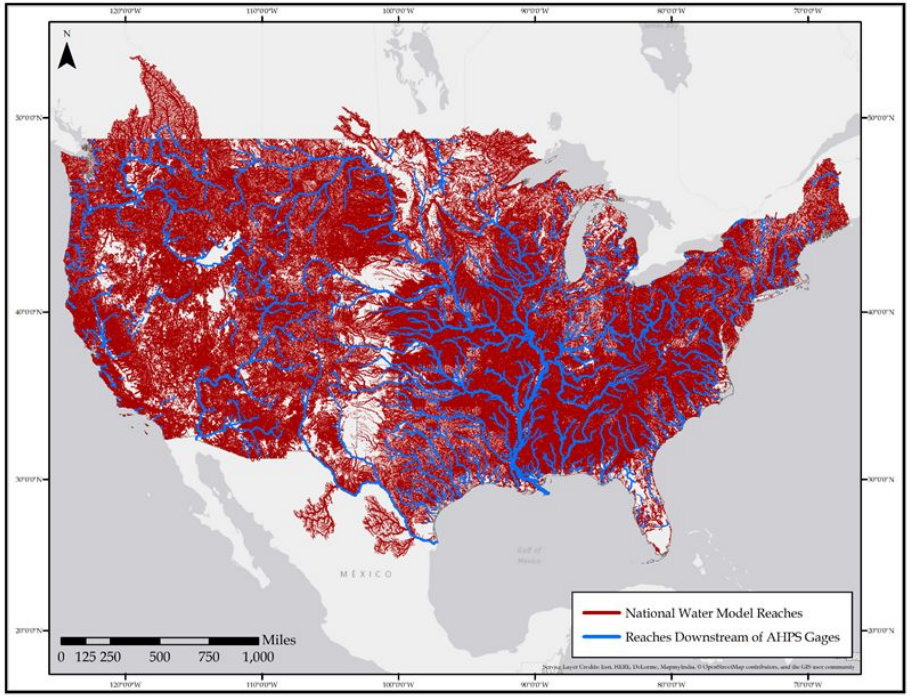
USGS science for a changing world

NOAA National Oceanic and Atmospheric Administration U.S. Department of Commerce

National Water Model

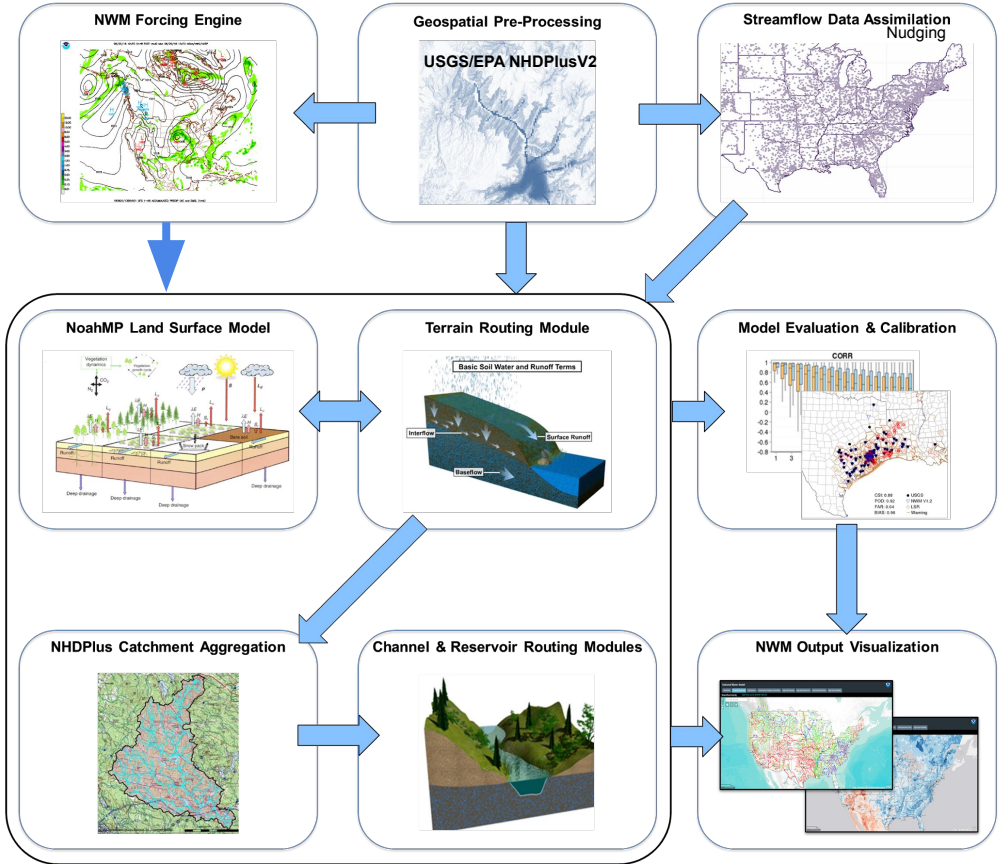
- **Continental-scale water resources model providing high resolution, spatially continuous estimates of major water cycle components**

- **Operational forecast streamflow guidance for currently underserved locations: 110,000 River miles to nearly 5,000,000 River miles**



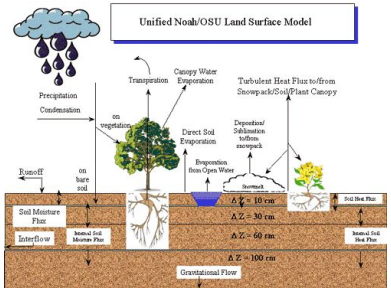
Current Operational NWM System Structure

NWM Hydrography
Medium Resolution
NHDPlusV2

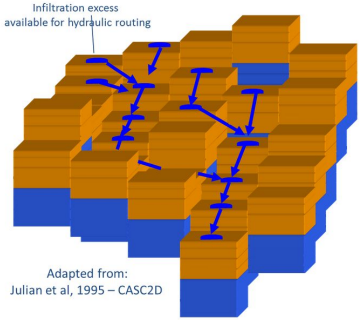


NWM Core Processes

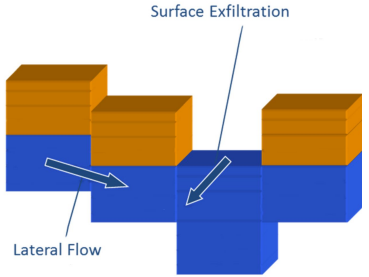
Column Hydrology: NoahMP



Overland Flow: 1D Diffusive Wave

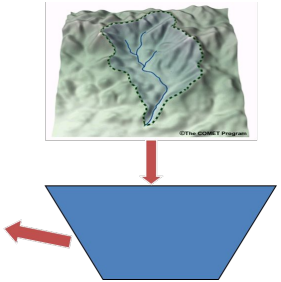


Lateral Subsurface Flow: 2D Boussinesq

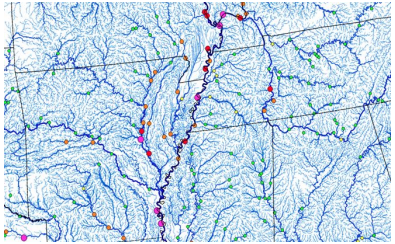


Adapted from:
Prickett-Lonnquist, 1971

Baseflow: Conceptual Nonlinear Reservoir



Channel Routing: Vector-based Muskingum-Cunge



Basic Water Management: Fill and Spill Reservoir

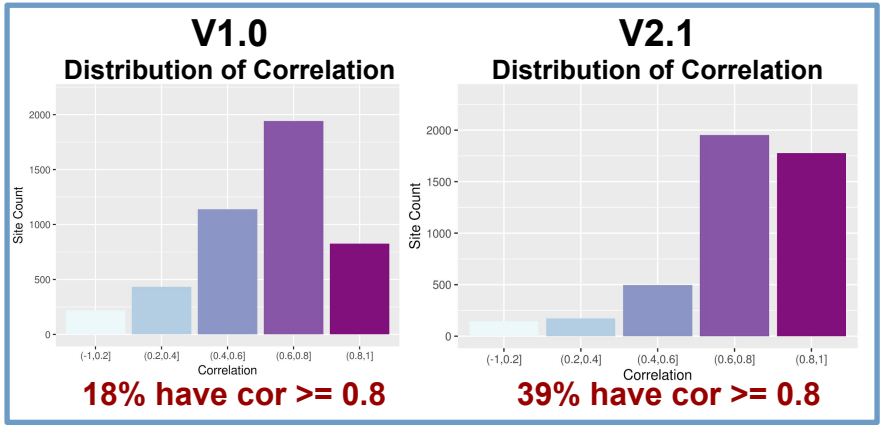
NWM Development Trajectory

v1.0 → v1.1/1.2/2.0 → v2.1

Foundation: 2016
Water resource model
2.7 million reaches

Upgrades: 2017/2018/2019
Hawaii, medium range ens., physics upgrades, improved modularity, MPE ingest

Next Upgrade: Early 2021
Expansion to PR and Great Lakes, reservoir modules, forcing upgrades, open-loop, and improved Hawaii forcing



v3.0

Future Upgrade: 2022
Coastal coupling, expansion to Alaska, improved infiltration, inland hydraulic routing, hydro-fabric upgrades

Community Advisory Committee for Water Prediction

2019 Report Recommendations:

1. Articulation of requirements for further development of the NWM; articulation and communication of process, procedures, and definition for areas for potential community contribution.
2. Emphasis on improvement for observational data and potential sources of data.
3. Emphasis on improving data assimilation techniques and processes. Conduct gaps analysis of NWM operations for identification of areas that could benefit from more observations (e.g., data assimilation).
4. Stand up a community development engagement process, governance, and center; pursue proven mechanisms for community adoption:
    a. Development of sustaining communication and dissemination activity to advance understanding of the NWM, its operational priorities, and the creation of an infrastructure and connective tissue for a developmental R&D instantiation.
    b. Foster community participation via an AGU Chapman Conference convening or other opportunities for sustained interaction between the academic research and development community and the NWM.
    c. Develop guidelines for interaction; make public a software roadmap and development plan for the NWM; establish metadata and quality control.
    d. Strengthen more formal partnerships with the private sector.

GSA 18F Recommendations

1. Working code is the best way to determine the path forward.
2. Develop a team and leadership structure to support acting on a unified vision and direction.
3. Borrow from industry open source development practices.
4. Treat interfaces as products.
5. Build for sustained development over multiple years and changing team members.
6. Understand and celebrate the NWM community.

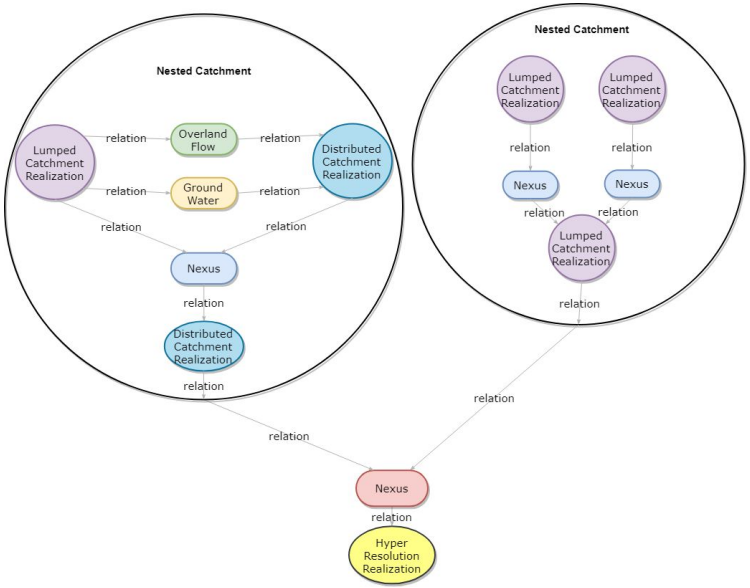
Design Workshop - July 2019

What it is:

Framework for describing connected models that apply established and appropriate methods for watersheds of various sizes or at different times. Modeling system built on standard community hydrologic geospatial data.

What it does:

1. Allows addition of any appropriate model (formulation, programming language, or structure) for any sub-watershed by implementing framework interfaces.
2. Enables integration of hyper-resolution models into the [Modeling System].
3. Implements recognized concepts vetted through a community standards process.
4. Allows the methods used to calculate hydrologic variables to vary in space and time.
5. Allows for consideration of different methods for calculating responses of watersheds.
6. Supports exchange of information between internal models and manages standardized input and output for the entire model.
7. Uses well established methods (graph theory) to manage order of execution and communication of component watersheds.

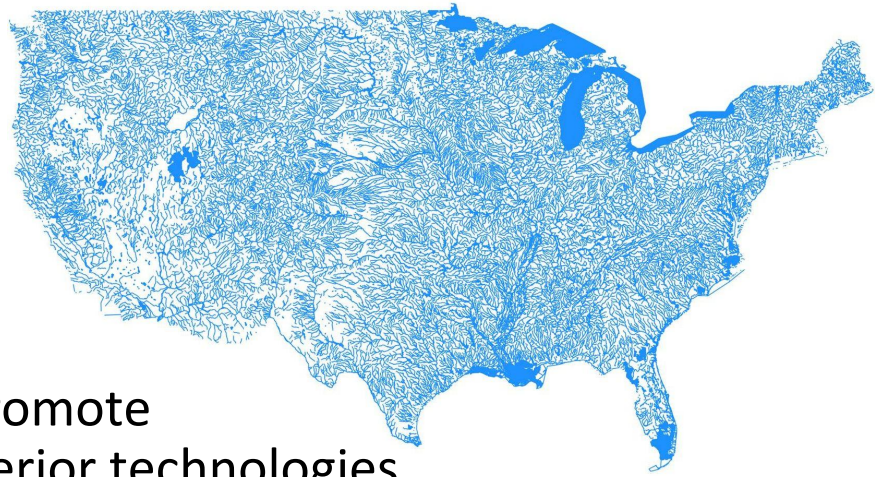


Motivation

- Federal agencies struggle with model selection, identifiability and interoperability
- Legacy codes and heterogeneous computing environments impede advances
- Contemporary open-source software paradigm encourages collaboration, evidence-based selection, identifiability, and promotes interoperability
- Example: NOAA-NWS requirements to protect life and property on NHD+ coincides with domains of other federal agencies

Common Need

- The National Hydrology Dataset (NHD+ V2.0) provides a consistent representation of US drainage network
- This representation forms an natural focus for agencies with different:
  - Missions
  - Modeling needs
  - Space/time scales of interest
- A computational system that supports these needs and interacts with this domain will promote collaboration and the use of superior technologies



Proposed Solution

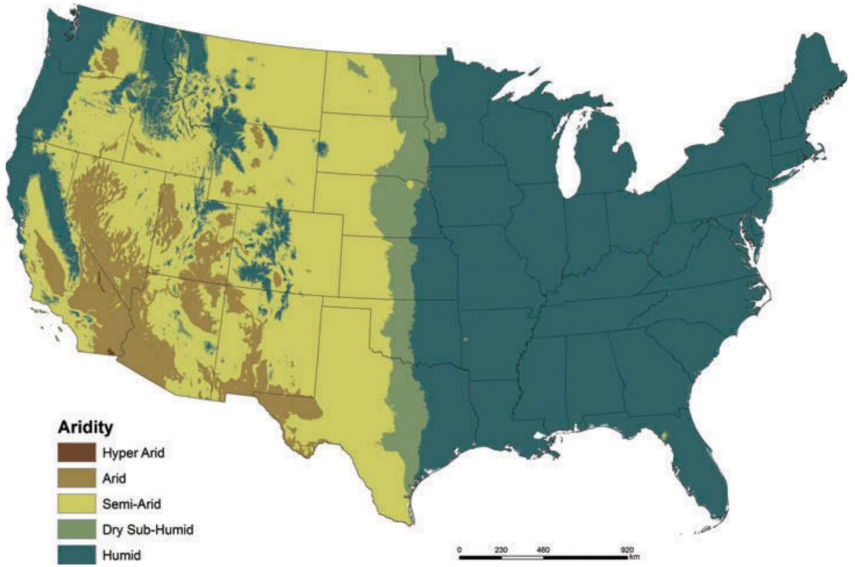
- Develop a computational framework that allows arbitrary methods/models to simulate fluxes of interest and integrate them over arbitrary time scales and control volumes
  - Environment to appeal to domain scientists
  - Contemporary open-source software development methods
  - Provide maximum flexibility
  - Ease model interoperability
  - Allow evidence-based evaluation of different approaches
  - Take advantage of each agency's considerable experience

Justification

- Different hydrologic landscapes have different dominant processes
  - Affects hydrologic predictability criteria
  - No model works equally well everywhere at all times
  - In most locations surface and subsurface parameters are highly uncertain, creating a parameter estimation challenge
  - The literature clearly demonstrates that appropriately applied models with fewer parameters outperform models with more parameters in all but the best studied catchments
  - Modeling success results from acknowledging the dominant influences of uncertainty and heterogeneities from the perspective of dominant processes and predictability

Role of Groundwater

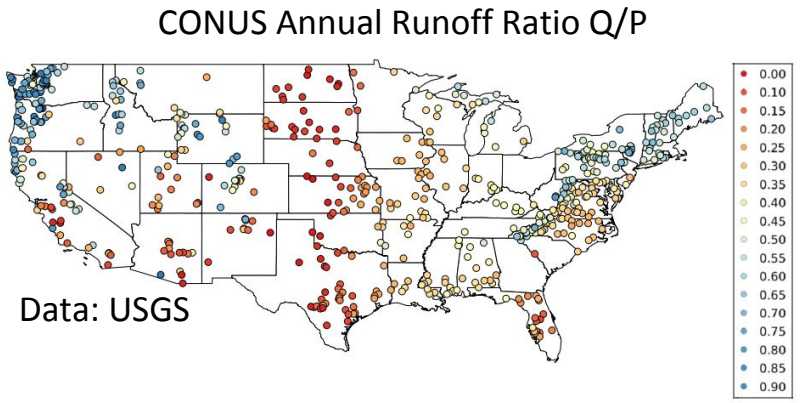
- Aridity index has a dominant influence on depth to water table
- When groundwater table is near the surface, hydrologic response a mostly a function of recent rainfall amount
- When groundwater table is far from surface, response tends to be rain-rate dependent

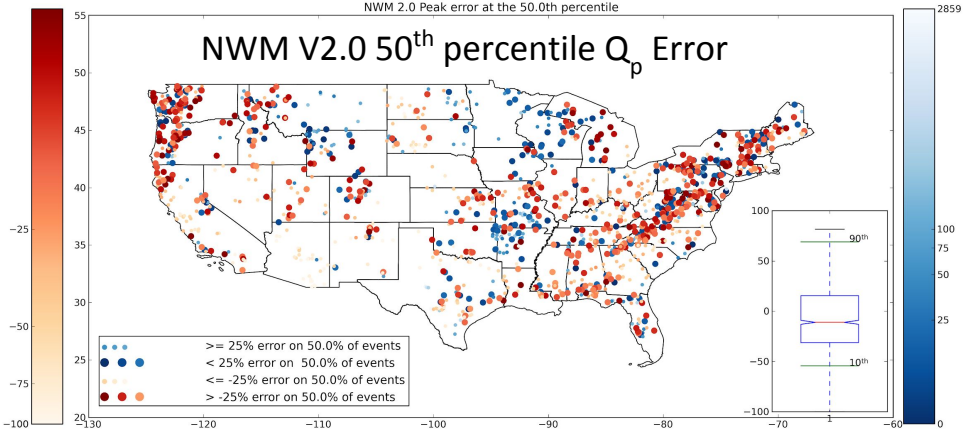


CONUS Aridity Index Map (Zomer et al. 2008)

Dominant Runoff Generation Mechanism

- Determined by:
  - Soils
  - Land use/cover
  - Rainfall rate
  - Freeze/thaw
  - Underlying geology
  - Antecedent precip.
- Places emphasis on different
  - Processes
  - Parameters
  - *Formulations*

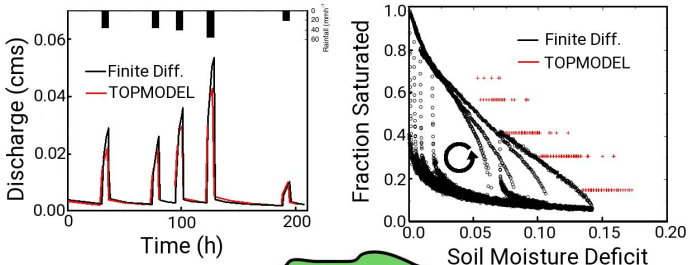


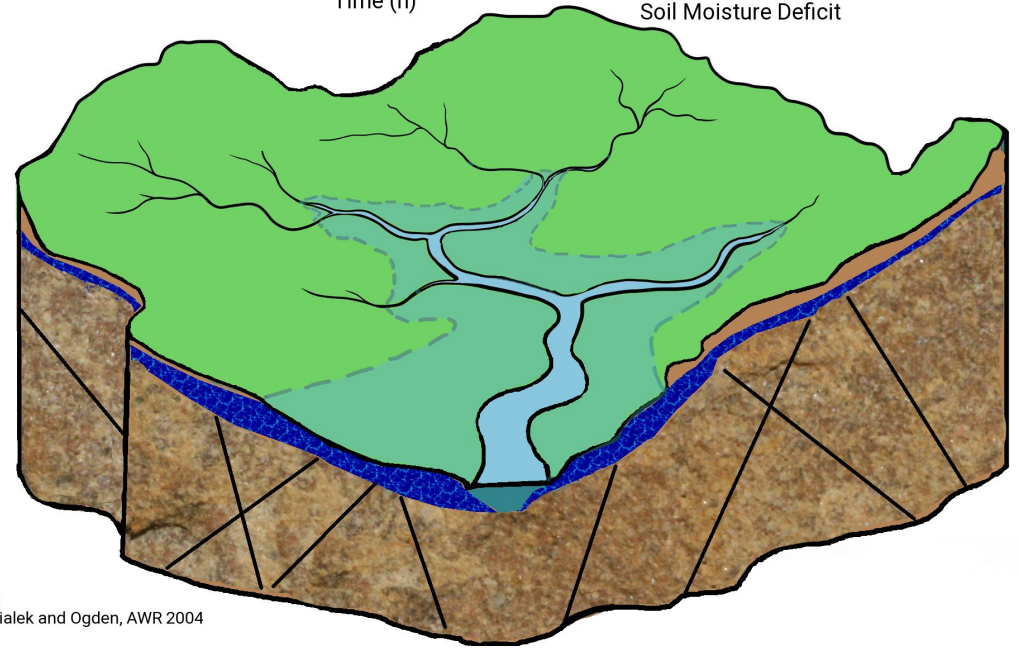


Facilitate Comparisons of Physical vs. Conceptual Models

Example: 2-D Finite Difference vs. TOPMODEL

- Hydrograph prediction compares well
  - Saves a lot of CPU cycles
- TOPMODEL does not simulate water table dynamics correctly
  - Is that important?





After:
Niedzialek and Ogden, AWR 2004

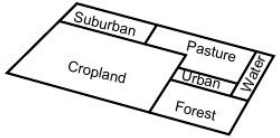
Note:

- This example is just one of many
- Surface and groundwater basins need not be coincident

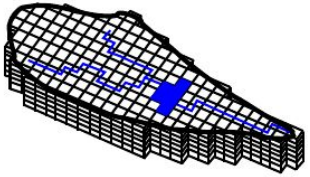
Diverse Model Formulations

Watershed

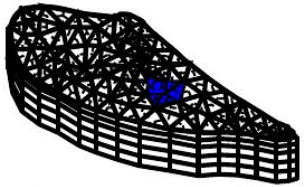
Hillslope



Tiled

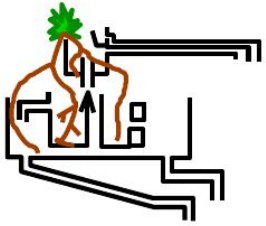


Structured

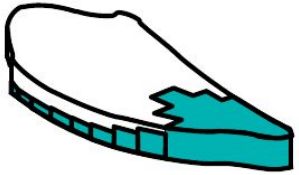


Unstructured/
Voronoi

Isochronous/
Stream Tube



Conceptual



Topo. Wetness Index

ML

Strategy

- Form two design working groups with a common coordinating group
  - Computer science
  - Domain science
- Identify agency/mission area specific needs. For example NOAA-NWS has identified:
  - Allow evidence-based evaluation of 3-10 km^2 catchment models over CONUS with hourly outputs on refactored NHD+ computational hydrofabric
  - Develop process-level libraries of:
    - Hourly or finer flux calculators (ET, Snowmelt, etc.)
    - Integrators/solvers (explicit FV, others)
  - Ability to support/test whole-model realizations
  - Compatibility with NWM forcing engine and outputs

Hydrologic Geospatial Fabric

Q: Why is flow at a gage affected only by its watershed?

Because hydrology.

Dave Blodgett
dblodgett@usgs.gov

USGS science for a changing world

NOAA National Oceanic and Atmospheric Administration U.S. Department of Commerce

Framing Questions

Engineering: What's your control volume and what are it's boundary conditions?

Internet: What's your resource and how does it link to other resources?

Software: What modules does your software have and how do they interact?

Data: What's your schema and how do its entities relate?

The answers to these are *highly* related.
We should all have a view for each.

What's been done?

20 years: National NHDPlus/Observations backbone

10 years: NHDPlusV2, hardened data services, computing for national model.

5 years: Running operational model capacity, updated annually.

1 year: Generate hydrologic geospatial fabric units at any resolution based on NHDPlusV2 with a path to NHDPlus High Res.
OWP, NCAR, USGS Planned NextGen architecture.

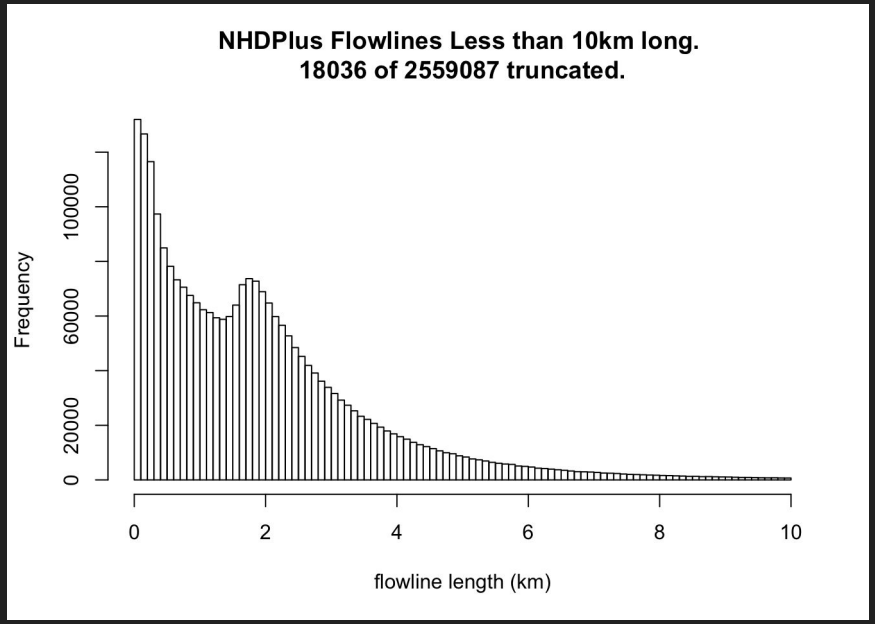
(Demo on following slides)

https://dblodgett-usgs.github.io/hyRefactor/dev/

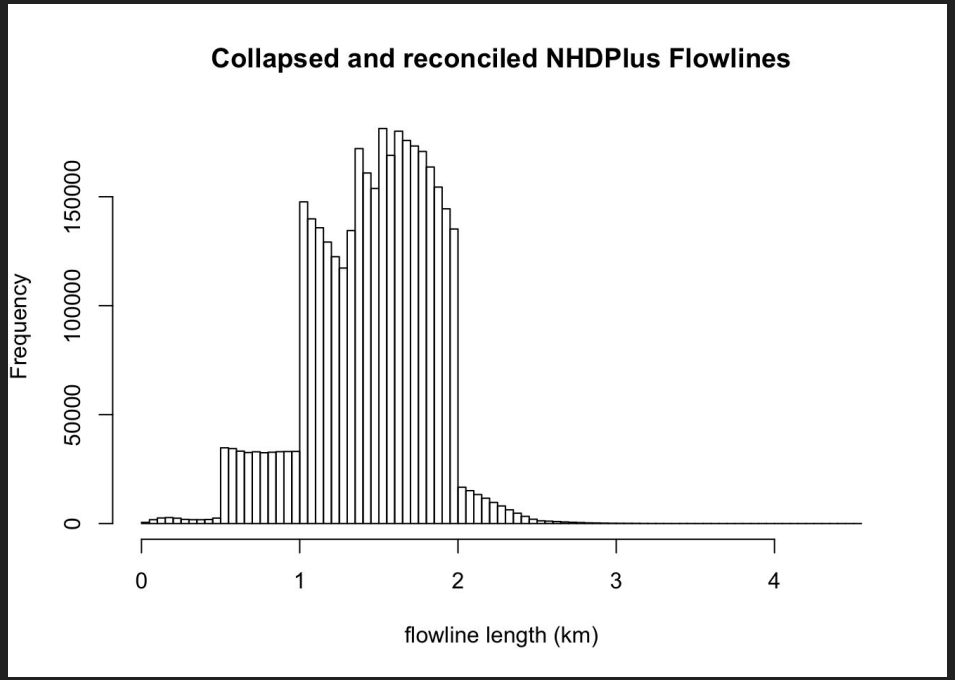
https://dblodgett-usgs.github.io/hygeo/dev/

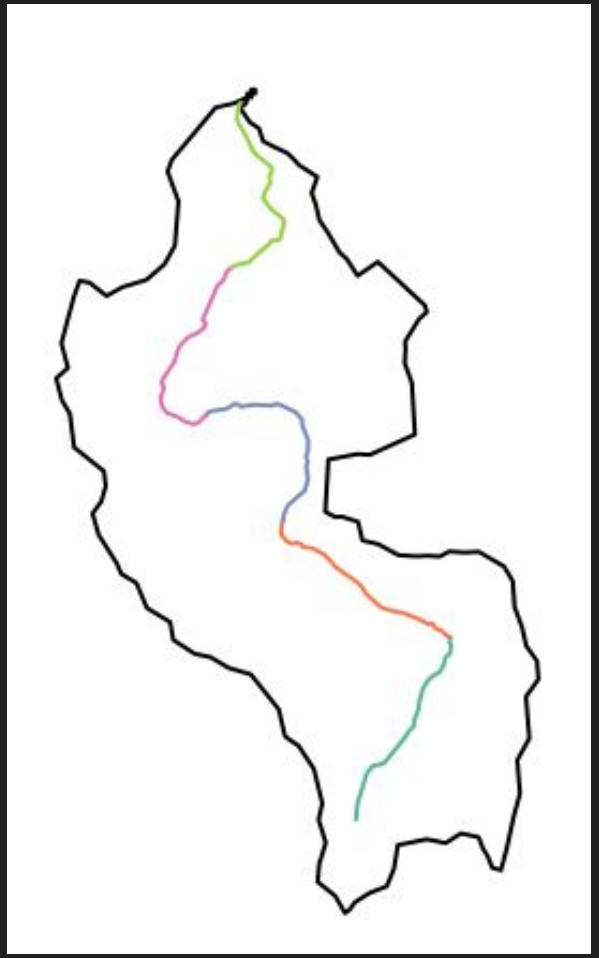
USGS science for a changing world

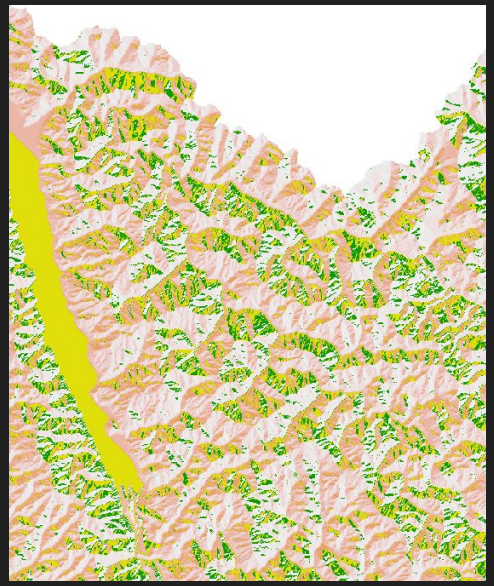
NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE



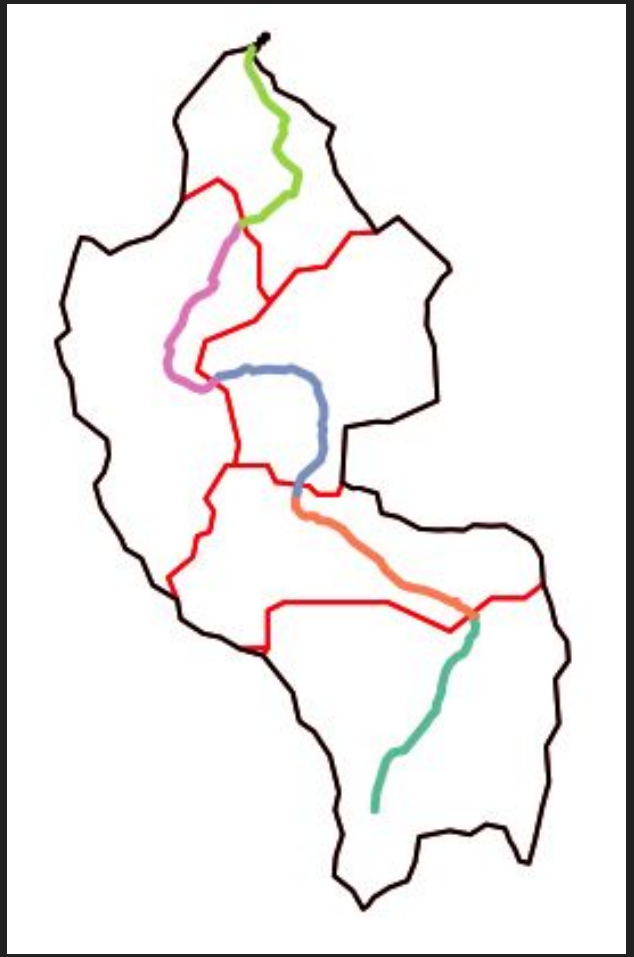
Refactor to change catchment size distribution

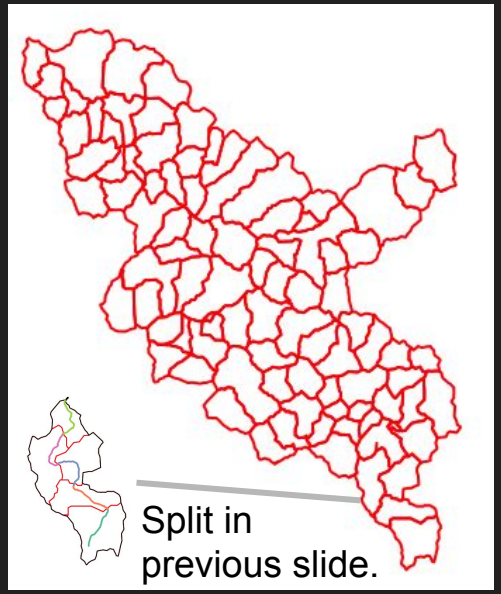




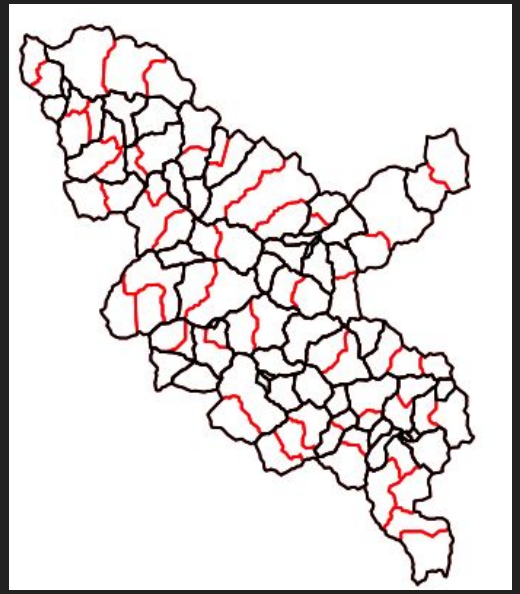


Split using flow direction and flow accumulation.

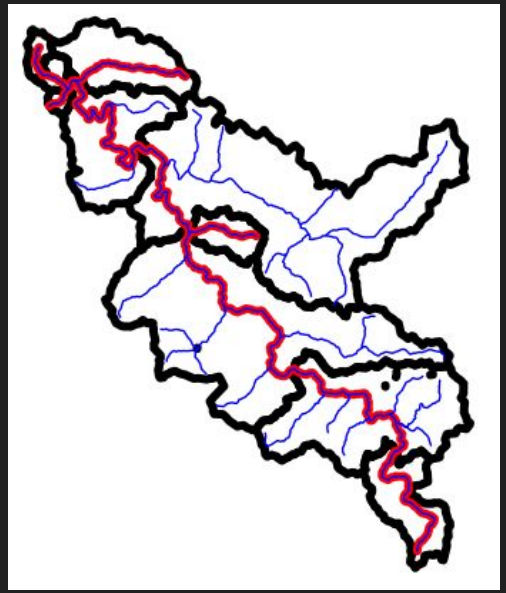




Split



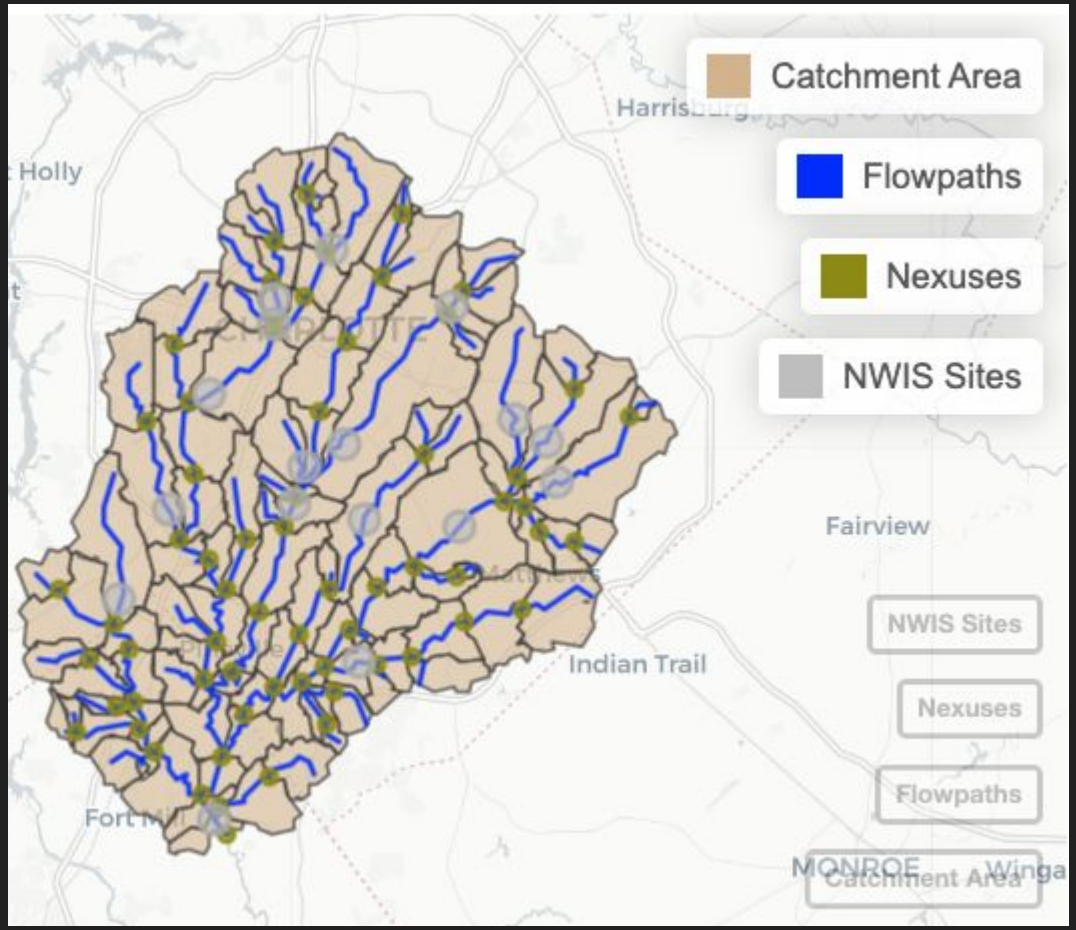
Collapse



Aggregate
and/or split

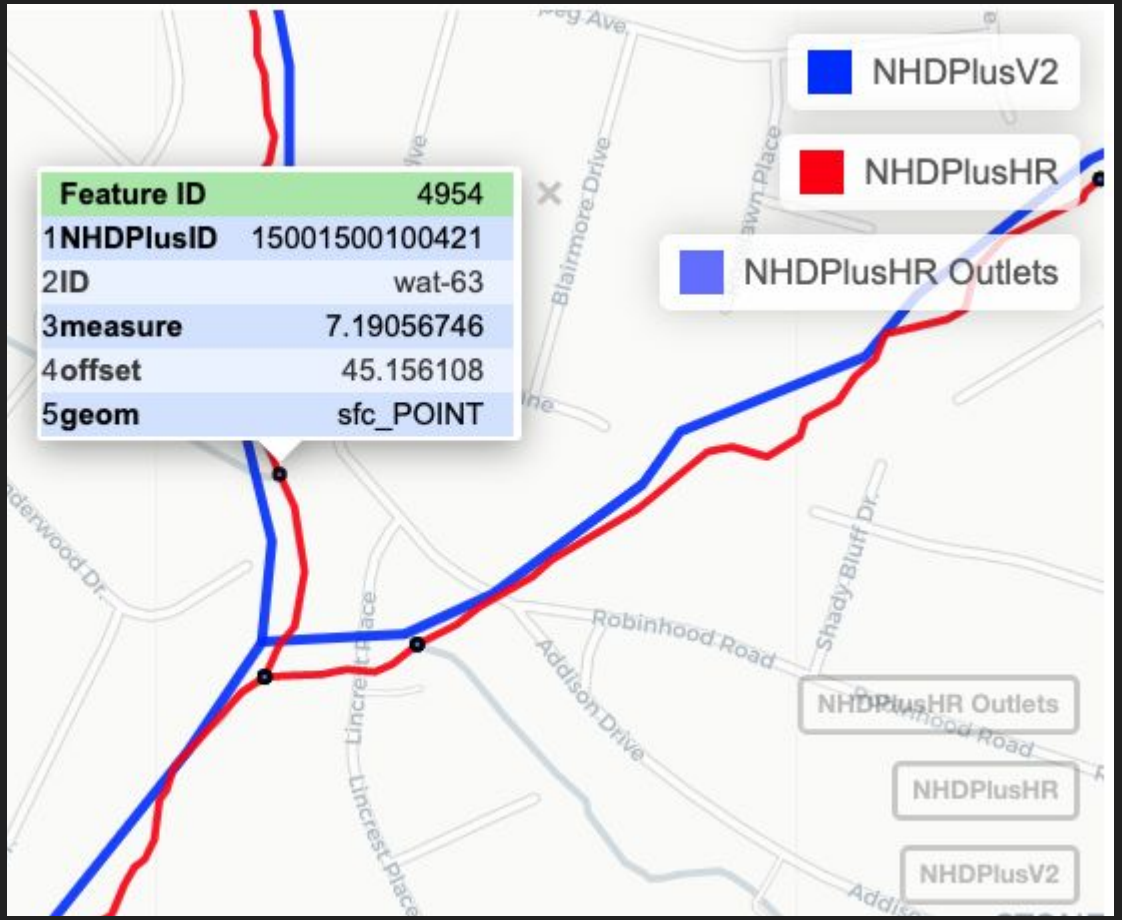
NGEN Release 1 Outcome:

Convert NHDPlus or hyRefactor output to NGEN framework input.



NGEN Release 2
So far:

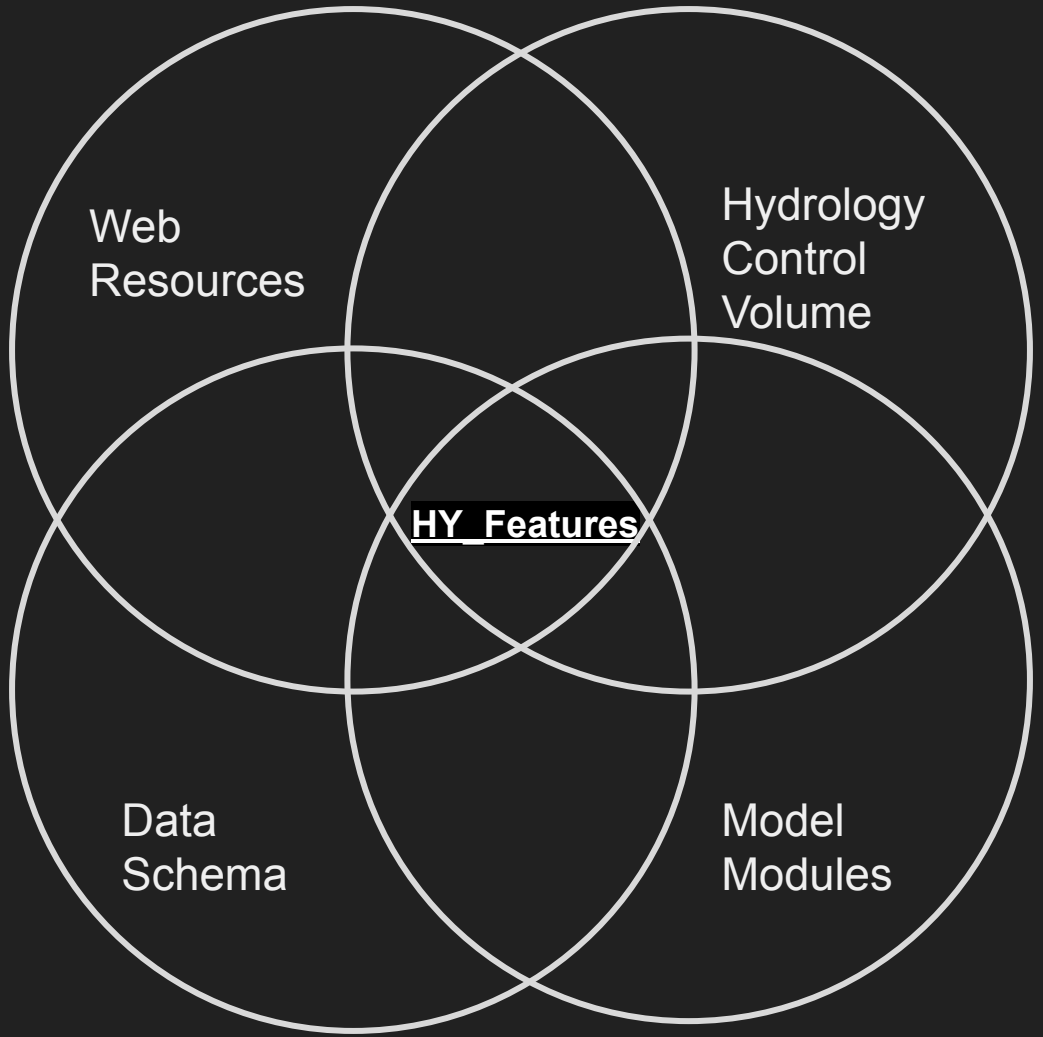
Integrate with
NHDPlusHR

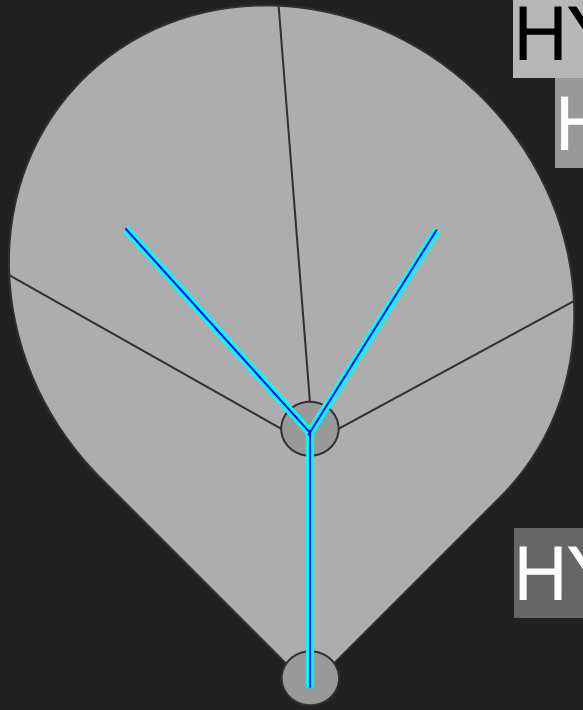


HY_Features defines concepts to be applied in all these domains.

Rooted in **observational hydrology**:

We measure or predict flow at a watershed outlet and that flow is the result of upstream processes.





HY_Catchment: Holistic

HY_CatchmentArea: Land surface

HY_FlowPath: Hydrologic Connectivity

HY_WaterBody: Lakes and Rivers

HY_HydroNexus: Catchment Interactions

USGS
science for a changing world

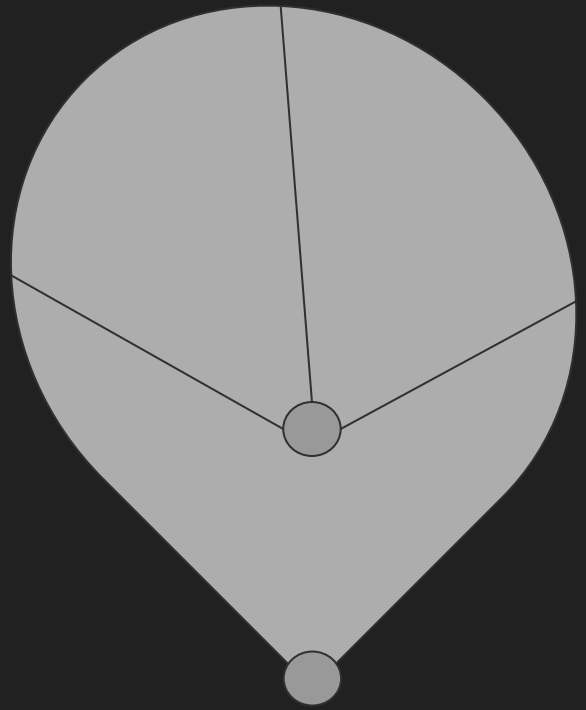
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

HY_Catchment / HY_HydroNexus

Holistic feature types track identity.

A catchment class* is "realized" by classes that do catchment stuff.

A nexus class is "realized" by classes that do nexus stuff.



*class is roughly equivalent to concept

Strategies for progress: Decompose the Problem

Decomposing the problem in two ways.

1) Spatial for social and engineering reasons.

2) Hydrology-concept for module composition.

Strategies for progress: Common Data Model

"Common data model" efficiencies.

Unique stuff with adapters to common stuff. GOOD

Unique stuff with adapters to unique stuff. BAD

Strategies for progress: Collaborate on Technology

Up our open-source development technical game as it relates to contribution. This is not easy -- need to invest in success

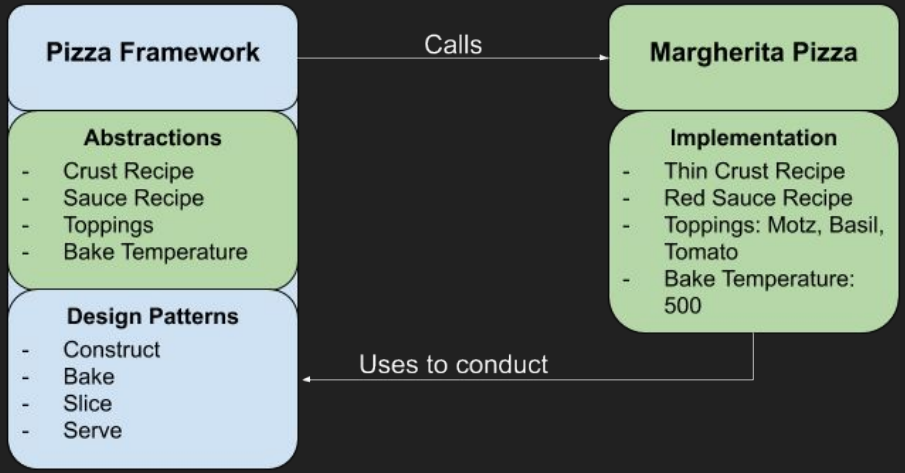
Own the problem we solve for stakeholders.

Share the technical solution.

Hydrologic Modeling Software Framework

“If applications are hard to design, and **toolkits (libraries)** are harder, then **frameworks** are hardest of all.” - GoF

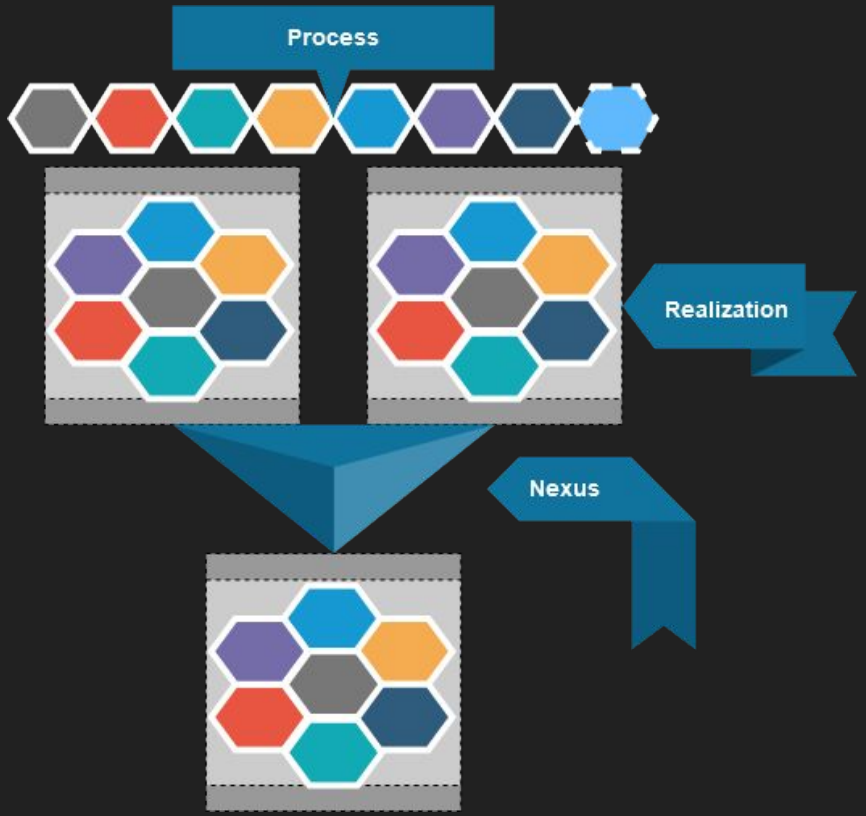
A **framework** is an abstraction in which software providing generic functionality can be selectively changed by additional user-written code, thus providing application-specific software.



Example framework

Software Engineering Best Practices

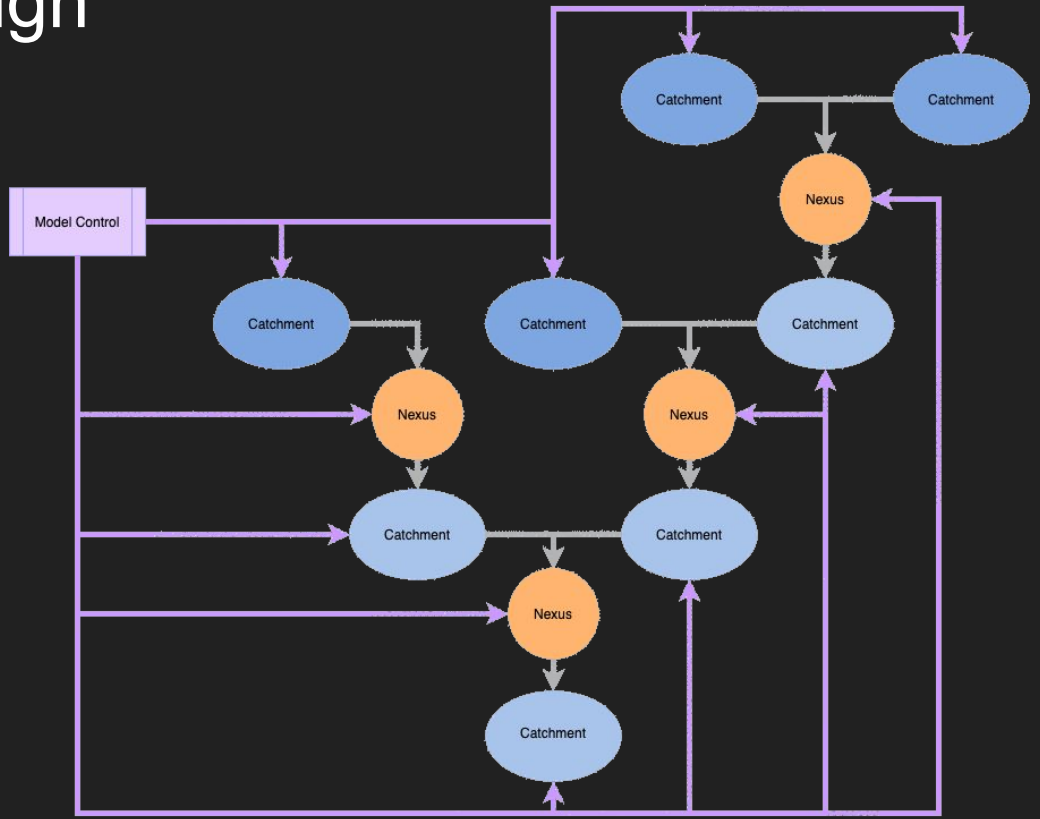
- Design Cohesive Component Interfaces
  - Cohesive: How well do the pieces fit together?
- Follow SOLID design principles
  - Maintainable and extensible code
- Implement flexible design patterns



Cohesive Interface Design

- Localization of changes
  - Including bug fixes
- Interchangeable modules
- Decentralized development
- Consistency
- **Independent implementation details!**

Note: In computer science, the word “cohesion” is a measure how well components of a module fit together. Cohesion promotes: readability, reliability, reusability, and robustness.



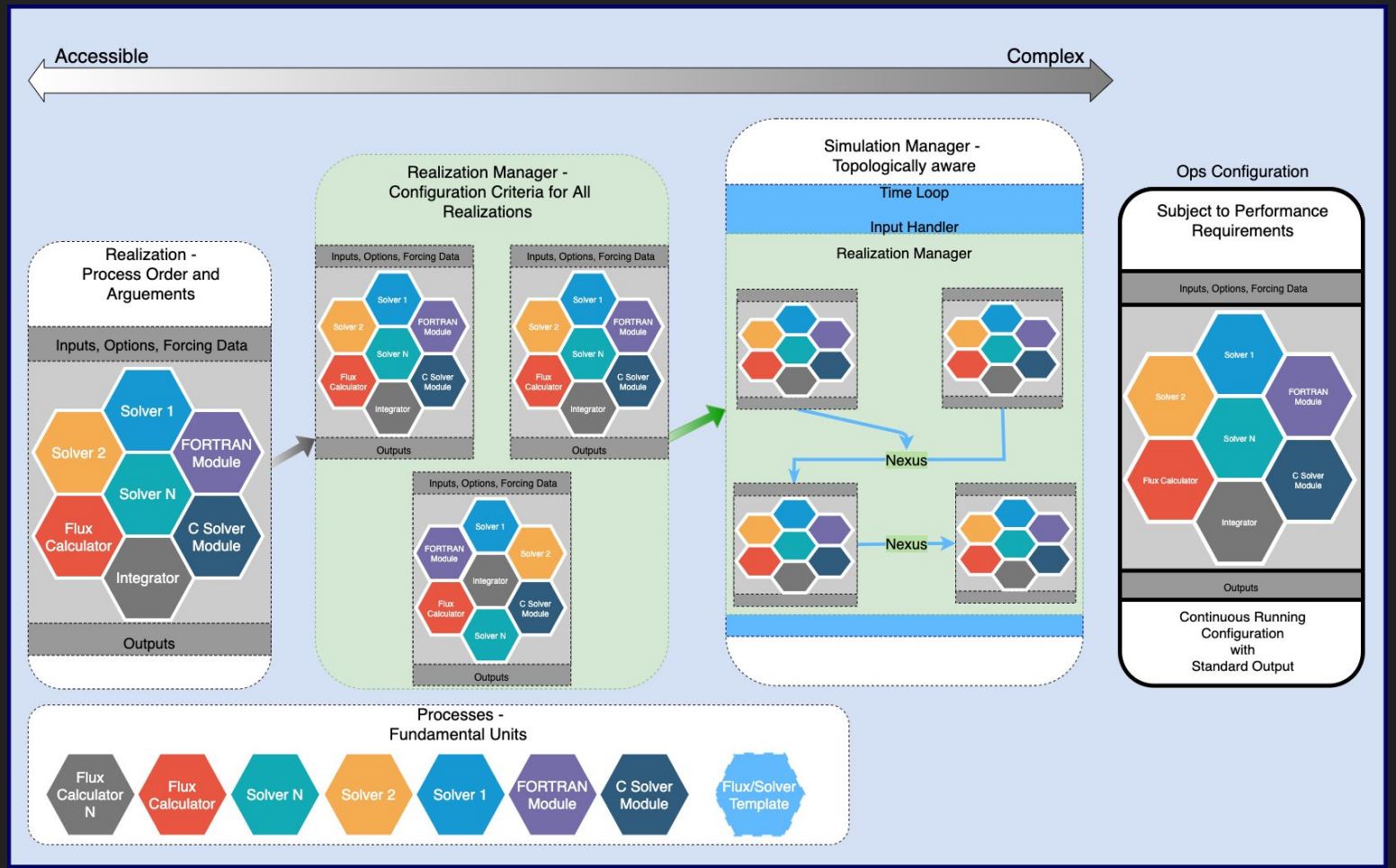
Decomposing the Problem: Abstract Interfaces

What data and functions does each component need from another component?

These functional and data dependencies form the basis for software interfaces which provide

- Encapsulation and composition
- Information partitioning and protection
- **Decouple the recipe, follow the basic steps**
- **Key to modularity and flexibility!**

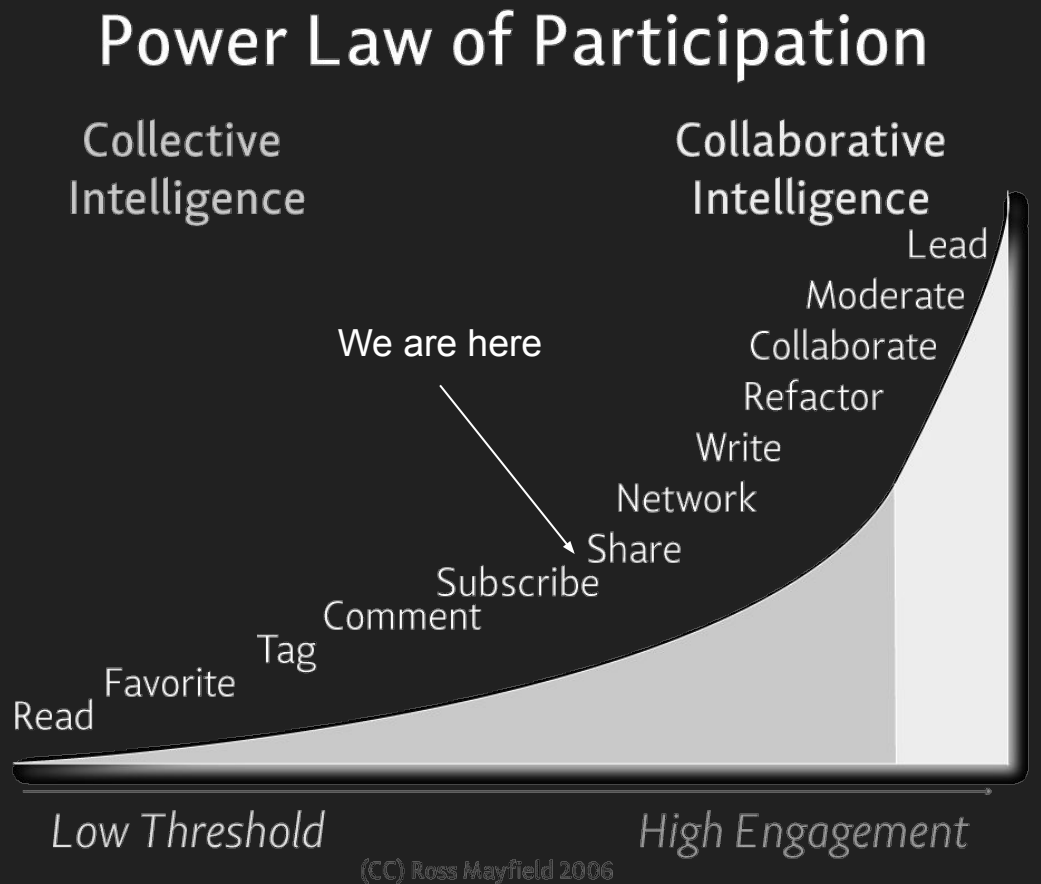
Framework Architecture



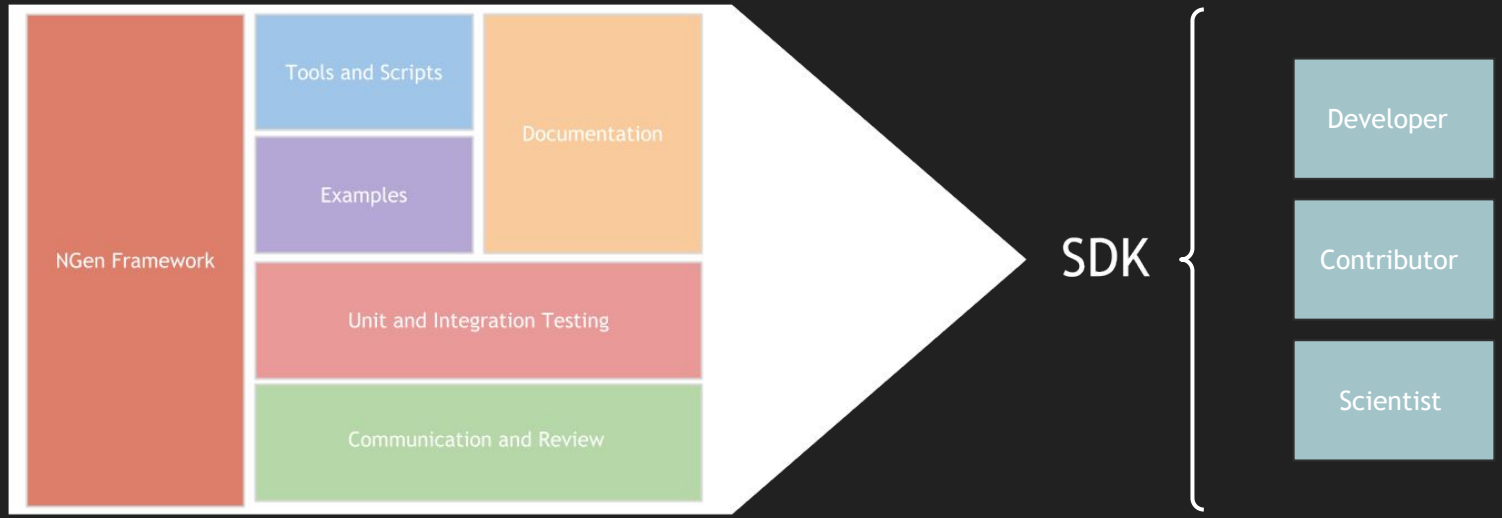
Community Foundations

Software Development Kit (SDK)

- Documentation
- Examples
- Tools and scripts
- Development environments
- Static code analysis
- Automated testing
- Rigorous yet inviting review



Software Development Kit (SDK)



Where Are We Now?

Initial Design and prototyping phases. Working on framework, tooling, and documentation.

https://noaa-owp.github.io/ngen/

https://github.com/NOAA-OWP/ngen

https://github.com/NOAA-OWP/ngen/actions?query=workflow%3A%22Testing+and+Validation%22

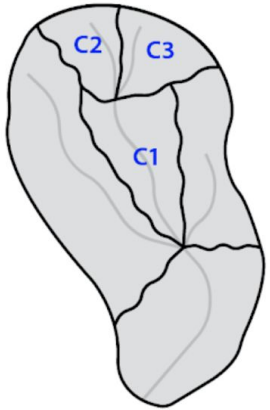
Next Gen Water Modeling Framework Prototype

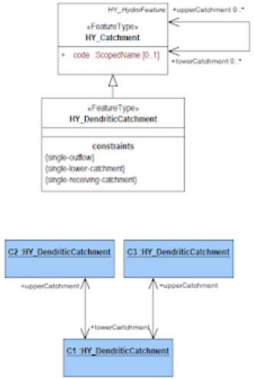
Description:
As we attempt to apply hydrological modeling at different scales, the traditional organizational structure and algorithms of model software begin to interfere with the ability of the model to represent complex and heterogeneous processes at appropriate scales. While it is possible to do so, the code becomes highly specialized, and reasoning about the model and its states becomes more difficult. Model implementations are often the result of taking for granted the availability of a particular form of data **and** solution – attempting to map the solution to that data. This framework takes a data centric approach, organizing the data first and mapping appropriate solutions to the existing data.

This framework includes an encapsulation strategy which focuses on the hydrologic data first, and then builds a functional abstraction of hydrologic behavior. This abstraction is naturally recursive, and unlocks a higher level of modeling and reasoning using computational modeling for hydrology. This is done by organizing model components along well-defined flow boundaries, and then implementing strict API's to define the movement of water amongst these components. This organization also allows control and orchestration of first-class model components to leverage more sophisticated programming techniques and data structures.

- **Technology stack**: Core Framework using C++ (minimum standard c++14) to provide polymorphic interfaces with reasonable systems integration.
- **Status**: Version 0.1.0 in initial development including interfaces, logical data model, and framework structure. See **CHANGELOG** for revision details.

Structural Diagrams





README.md

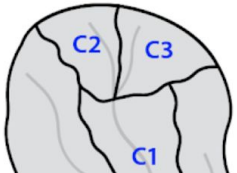
Next Gen Water Modeling Framework Prototype

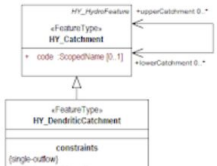
Description:
As we attempt to apply hydrological modeling at different scales, the traditional organizational structure and algorithms of model software begin to interfere with the ability of the model to represent complex and heterogeneous processes at appropriate scales. While it is possible to do so, the code becomes highly specialized, and reasoning about the model and its states becomes more difficult. Model implementations are often the result of taking for granted the availability of a particular form of data **and** solution -- attempting to map the solution to that data. This framework takes a data centric approach, organizing the data first and mapping appropriate solutions to the existing data.

This framework includes an encapsulation strategy which focuses on the hydrologic data first, and then builds a functional abstraction of hydrologic behavior. This abstraction is naturally recursive, and unlocks a higher level of modeling and reasoning using computational modeling for hydrology. This is done by organizing model components along well-defined flow boundaries, and then implementing strict API's to define the movement of water amongst these components. This organization also allows control and orchestration of first-class model components to leverage more sophisticated programming techniques and data structures.

- **Technology stack**: Core Framework using C++ (minimum standard c++14) to provide polymorphic interfaces with reasonable systems integration.
- **Status**: Version 0.1.0 in initial development including interfaces, logical data model, and framework structure. See CHANGELOG for revision details.

Structural Diagrams





NOAA-OWP / ngen

generated from NOAA-OWP/owp-open-source-project-template

Unwatch 13 | Unstar 11 | Fork 14

Code | Issues 8 | Pull requests 3 | Actions | Projects 1 | Wiki | Security | Insights | Settings

Workflows

New workflow

All workflows

Testing and Validation

Documentation

All workflows

Filter workflows

Event | Status | Branch | Actor

✓	**Initial version of Realization Configuration** Testing and Validation #27: Pull request #115 synchronize by christophertubbs	christophertubbs:config	6 days ago 3m 55s
✗	**Initial version of Realization Configuration** Testing and Validation #26: Pull request #115 synchronize by christophertubbs	christophertubbs:config	6 days ago 6m 19s
✗	**Initial version of Realization Configuration** Testing and Validation #25: Pull request #115 synchronize by christophertubbs	christophertubbs:config	6 days ago 2m 42s
✓	**Consolidated Reservoir Class and Linear Outlet** Testing and Validation #24: Pull request #117 synchronize by jdmattern-noaa	jdmattern-noaa:reservoir-…	8 days ago 3m 29s
✗	**Consolidated Reservoir Class and Linear Outlet** Testing and Validation #23: Pull request #117 opened by jdmattern-noaa	jdmattern-noaa:reservoir-…	8 days ago 3m 4s
✓	**Further Tshirt code refactoring** Testing and Validation #22: Pull request #116 opened by robertbartel	robertbartel:s5_refactor/…	11 days ago 4m 20s
✓	**added more nonlinear reservoir parameters to hymo...** Testing and Validation #21: Commit f8f14ac pushed by hellkite500	master	11 days ago 3m 52s

Strategy

Need working groups in multiple domains to continue progressing the design and implementation of this complex, yet well orchestrated framework!

Use cases and user stories to inform features and functionality.

Collaborative roadmapping of priority features in the **shared technical solution**.

Technical Contributions:

https://github.com/NOAA-OWP/ngen/blob/master/CONTRIBUTING.md