Hydrologic Monitoring and Prediction Systems
Requirements, Trade-offs, and Science

Andy Wood
National Center for Atmospheric Research (NCAR)
Research Applications Laboratory
Boulder, Colorado USA

WMO Global Hydrological Status and Outlook System (HydroSOS)
INITIAL PLANNING MEETING
Entebbe, Uganda – 27 Sep 2017
NCAR - a US National Science Foundation Center

Boulder, Colorado, USA

http://ncar.ucar.edu/

1400 staff:
~435 PhD/M*
~200 Engr/Soft

$200M budget
Board of 130 universities
Outline

- Hydrologic Predictability – Sub-seasonal to Seasonal
- US Hydrologic Prediction System Examples
- Perspective: Requirements / Tradeoffs / Science
Sources of S2S Hydrologic Predictability

**Hydrological predictability**

- How well can we estimate the amount of water stored on the land surface?
  - models
  - in situ obs
  - satellite obs

**Meteorological predictability**

- How well can we forecast the weather and climate?
  - dynamical models
  - empirical methods

Hydrological Prediction

Water Cycle (from NASA)
Hydrologic forecast outcomes include a signal from two major sources:
- initial land surface moisture conditions
- future weather and climate

**S2S Hydrologic Prediction**

**Past**  
**Future**

**Flow**

**Forecast Start**  
**Time**

- Initial condition signal (given expected climate)
- Future weather/climate uncertainty
Predictability sources vary

- Little predictability from land surface moisture conditions
- Most predictability depends on future climate

Wood & Lettenmaier, 2008, GRL.
Predictability sources vary

- 4-6 months of predictability from land surface moisture conditions
- Little predictability from future climate

Wood & Lettenmaier, 2008, GRL.
Take-away

Participating Systems (NHMS) should be able to harness both sources of predictability
Outline

- Hydrologic Predictability – Sub-seasonal to Seasonal
- US Hydrologic Prediction System Examples
- Perspective: Requirements / Tradeoffs / Science
Uncoupled systems – derive forcing meteorology from external sources

Most have a similar set of data, model and method components

The choices for each component lead to far different capabilities
Selecting a Forecasting Paradigm

Various Paradigms to Consider

• Medium-resolution / Ensemble / Regional / Uncoupled
  • UW Surface Water Monitor
  • Princeton African Drought Monitor

• High-resolution / Deterministic / Uncoupled
  • Example: US National Water Model
Coarse-scale, Agile Hydrologic Prediction Systems

- VIC ½-degree ensemble prediction with ~100-year archive for prior simulation, daily updates
- **Hurdles:** may be difficult to relate to fine-scale local variables; no water management

See Wood, A., 2008, AMS Proceedings
Ensemble systems can support probabilistic products

Probability of Recovery to Normal 3-month runoff
VIC ¼ degree resolution modeling internationally; 1/8th degree in the US
Hindcast-able systems support useful capabilities

- Multiple forecast or model combinations based on skill
  - Land-surface dynamical predictions
  - Statistical Forecasts using Climate

- Verification

Oct 1 Forecast/Hindcast, May-Sep Runoff
Method: Statistical (indices)

Hungry Horse Reservoir, MT
A new Water Center opened in the US (2015)

National Water Center

- NOAA is constructing the IWRSS National Water Center (NWC) at the University of Alabama, Tuscaloosa.
  - 58,000 SF facility (full occupancy = 200)

- Components
  - operations center for water analysis, forecasting and decision support
  - applied water resources research and development center
  - geo-intelligence laboratory
  - distance-learning center
Actionable Water Intelligence
Global to Street Scale

Where?

GLOBAL
NATIONAL ➔ REGIONAL
WATERSHED
STREET
• 250m resol.: output for 2.7 million stream reaches, with hourly timestep, deterministic
• Computing: one 25-year full-resolution run on 2000 CPUs can take over a month
• **Hurdles:** calibration, ensembles, data assimilation, verification, longer-range forecasts
System Design Tradeoffs

Given Fixed Resources...

Legend
- green: traditional
- red: hyper-resolution
- blue: ensembles
- orange: nwp routing

- model process or forecast workflow complexity
- space/time resolution
- space/time domain
- ensemble techniques (uncertainty quantification and reduction)
Outline

• Hydrologic Predictability – Sub-seasonal to Seasonal

• US Hydrologic Prediction System Examples

• Perspective: Requirements / Tradeoffs / Science
System requirements depend on user needs

**Short-range** (hours to days)
- Watch and warning programs
- Local emergency management activities
- Flood control and energy system management
- Water deliveries (irrigation)

**Medium-range** (1-2 weeks)
- Reservoir management
- Local emergency management preparedness
- Coordinated regional operations
- Water deliveries (irrigation)

**Long-range** (3 weeks to months)
- Water supply planning
- Reservoir system management
- Agriculture, Navigation, Energy, and other
US hydroclimates and water uses drive user needs

Precipitation 1971-2000

'water supply forecasts'
Snowmelt, dry summers
1-5 year lead times
large reservoirs

'runoff outlooks'
1-3 months lead times
Little to no snow
No dry season
smaller reservoirs
Scientific considerations are critical

- Both User Needs and Science should inform product requirements
- Product requirements then determine system design
- System design is limited only by technical feasibility / resources
- But system quality, utility and value are limited by the science

Possible Implications for HydroSOS, e.g.,:

- **USER**: S2S predictions (uncertain) should quantify uncertainty and allow for verification, maybe downstream decision system support
- **SCI**: Quality control though verification and post-processing are needed — require hindcasting? How to validate?
- **SCI**: Data assimilation & model calibration are beneficial – both require system agility (ability to run system 100s-1000s of times)
- **SCI**: S2S prediction lead time means both initial land surface conditions and future weather / climate must be included.
- **FEAS**: Need for uncertainty quantification suggests agile hydrological analysis and prediction approaches (computing not unlimited)
Protocols will be a central task

HydroSOS will likely incorporate predictions from NHMSs

• If so, a protocol will be needed to standardize inputs/services to HydroSOS
• Example – the US National Multi-model Ensemble (NMME) Climate Prediction System

A protocol specifies

• The requirements for NHMS information products
• Examples -- lead times, latency, quality markers, hindcast lengths, resolution (time/space), variables, update frequency, …
• Protocols can be multi-level (eg, tiers of quality)

NMME Phase-I Hindcast and Real-time Experimental Prediction Protocol

The CY2011 NMME experimental predictions have been made in real-time since August 2011. As part of the development of the real-time capability, the NMME partners agreed on a hindcast and real-time prediction protocol. Some of the key elements of this protocol include:

• Real-time IS1 prediction system must be identical to the system used to produce hindcasts. This necessarily includes the procedure for initializing the prediction system. The number of ensemble members per forecast, however, can be larger for the real-time system.

• Hindcast start times must include all 12 calendar months, but the specific day of the month or the ensemble generation strategy is left open to the forecast provider.

• Lead-times up to 9 months are required, but longer leads are encouraged.

• The target hindcast period is 30 years (typically 1981-2010).

• The ensemble size is left open to the forecast provider, but larger ensembles are considered better.

• Data distributed must include each ensemble member (not the ensemble mean). Total fields are required (i.e., systematic error corrections to be coordinated by MME combination lead, NOAA/CPC). Forecast providers are welcome to also provide bias-corrected forecasts and
Talk Summary

User Needs

Scientific Considerations

Information Product Requirements

Protocol(s)

NHMSs or WMO

System Requirements
Thank You

Contact: AndyWood@ucar.edu
**A Coupled NWP-based Hydrologic Forecast System -- GEM-Hydro**

- No offline hydrologic forecasting component (but land can be calibrated offline)
- Intermediate scale LSM (10 km) with high resolution channel routing (1 km)
- Consistent model states and fluxes (precipitation, evaporation, runoff)
- **Hurdles**: more complicated to develop/improve (must fit NWP system R&D priorities)
Implementation Questions

• What dedicated computing will be available (CPUs, esp. data storage)
• Will there be a separate/similar development system or environment?
• Will codes be available/curated in public repositories (e.g., Github)?
• How will the system dev. & operations be managed and codes maintained (governance – core team – funded, volunteer?)
• Hosted datasets vs external datasets (e.g., obtained via web services)
• Outreach and training materials and effort?
• Service/Product specs: latency, update frequency, resolution, vars, …
• How to build reliability (given input dataset intermittency or evolution)
• How to determine quality (hindcasting?) and communicate it?
• Will key target sectors be involved in guiding development?
  • It’s important to develop ‘Use Cases’ early in process
• How will analyses and forecasts be disseminated? (centrally, to NHMSs?)
• Will the starting system design point be:
  • An existing global system (e.g., GLOFAS / CFSv2 / NMME)
  • Existing regional system(s) that will be extended to cover new regions?
Scientific considerations are critical

- Both User Needs and Science drive system requirements
- System requirements drive system design
- System design is limited only by technical feasibility
- But -- *system quality, utility and value* are limited by scientific capabilities

**Example**

- Flash Flood Prediction
  - **User Requirements** – high space time resolution, high-update frequency
  - **Science**: At highly saturated conditions, modeling weaknesses are less important than overland flow routing
    - Data assimilation and model calibration are less critical than for longer-lead prediction (eg for reservoir inflows)
    - Hindcasting & post-processing is more important for meteorological ensembles
  - **Science**: Uncertainties at fine resolutions recommend ensembles
  - **Feasibility**: Short lead times (<2 days) allow for high resolution+ensembles
My Background in Hydrologic Prediction

• **2004-2008** – Research assistant professor – built & ran real-time streamflow and CONUS-wide drought prediction systems (U. Washington, Seattle)
• **2008-2010** – Sr./Lead Scientist – managed science team researching real-time forecasting capabilities for renewable energy clients – hydropower, solar, wind (3TIER, Seattle)
• **2010-2013** – Development and Operations Hydrologist (DOH), infusing new science and helping manage operational streamflow forecast teams for regional NWS Colorado and Northwest River Forecast Centers
  • major writer, *Requirements* document for NWS Hydrologic Ensemble Forecast Service (HEFS)
  • *Short Term Water Management Decisions* document (NOAA, USACE, Reclamation)
• **2013-present** – Project Scientist, focusing on hydrologic applications – prediction, climate change, drought, S2S forecasting

Advisory/Service

• Co-Lead, international *Hydrologic Ensemble Prediction Experiment (HEPEX)*
• Editor at Amer. Met. Society (AMS) *Journal of Hydrometeorology*
• Chair (former), AMS Hydrology Committee and Annual Conferences (2011-2013)
• Advisory Boards/ Panels:
  • EU Horizon2020 *Improving Prediction of Hydrologic Extremes* (IMPREX)
  • ECWMF European and Global Flood Awareness Systems (EFAS/GLOFAS)
  • US CLIVAR Prediction, Projection and Applications Interface (PPAI) panel

1. Does the HydroSOS need to interact with existing IT infrastructure and systems, and if so, which ones (e.g. WIGOS/WHOS) and how?

2. How important are issues such as open source technologies, development, maintenance and licensing costs for such systems?

3. How might we best establish the required IT infrastructure and specifications for the HydroSOS at global, region and national scales – what are the key constraints and opportunities?

4. How can sustainability and continued data sharing be assured for HydroSOS?

5. How could the design of HydroSOS system be influenced by the way national hydrological and meteorological services are delivered in various countries? How could we cater to the requirements where national meteorology and hydrology services are delivered through different agencies?
Based on a WRF-Hydro Modeling System Configuration

Column Land Surface Models:
Noah/NoahMP/SAC-HTET

1-km resolution
Evapotranspiration
Soil moisture/Soil Ice
Snowpack/snowmelt
Runoff
Radiation Exchange
Energy Fluxes
Plant Water Stress

2-way coupling

1-way coupling or 2-way coupling

Terrain Routing Models:
Overland, subsurface flow

Stream Inflow, Inundation Depth, Groundwater Depth, Soil Moisture

250-m resolution

NCAR Lead: Dave Gochis

Channel & Reservoir Routing Models:
Hydrologic and Hydraulic

250-m

Streamflow
River Stage
Flow Velocity
Reservoir
Storage & Discharge

NCAR UCAR
Hydrologic Prediction with the Community WRF-Hydro System
Hydrologic Prediction with the Community WRF-Hydro System

National Water Model (NWM) Configurations

**WRF-Hydro Configuration**

- **Analysis & Assimilation**
- **Short Range**
- **Medium Range**
- **Long Range**

**Update Frequency**
- **Hourly**
- **Hourly**
- **4X Daily**
- **Daily (x16)**

**Forecast Duration (Lead Times)**
- **- 3 hrs**
- **0-12 hrs**
- **0-10 days**
- **0-30 days**

**Spatial Discretization**
- **1 km / 250m / NHDPlus reach**
- **1 km / 250m / NHDPlus reach**
- **1 km / 250m / NHDPlus reach**
- **1 km / NHDPlus reach**

**Meteorological Forcing**
- **MRMS blend/ HRRR**
- **Downscaled HRRR/RAP blend**
- **Downscaled GFS**
- **Downscaled & Bias-Corrected CFS**
The Real-time Prototype at NCAR

Daily updating website

Precipitation & Temperature Forecast Anomalies
  CFSv2
  NMME

next Official?

S2S periods
  bi-weekly
  monthly

Skill assessments for current data products

Soon: Data Downloads