Seasonal hydrologic forecasting and use for water management in the United States
-- current practice and future potential

Andy Wood
NCAR Research Applications Laboratory
Boulder, Colorado

BfG / WMO / IHP-HWRP Secretariat
Seasonal Forecasting – Current Challenges and Potential Benefits for Decision Making in the Water Sector
Koblenz, Germany, Oct 15 2014
HEPEX – International Seasonal Forecasting Experiment?

HEPEX and GEWEX GHP have been discussing a cross-cutting project to advance seasonal hydroclimate forecasting
- an intercomparison experiment?
- ideas welcome!

**GEWEX RHPs**
Improving scientific understanding of regionally significant features
water & energy cycle, leading to:
- Better models
- Better datasets

**HEPEX**
Applying improved scientific understanding, data and models to improve operational prediction of floods and droughts

**Operational Prediction**
HEPEX methods filtering into operations for
- Water/energy management
- Hazard mitigation
Outline

Operational Forecasting – western US
  objectives
  processes
Opportunities for Improvement
Recommendations
Many droughts will occur; many seasons in a long series will be fruitless; and it may be doubted whether, on the whole, agriculture will prove remunerative.

John Wesley Powell, 1879
Report on the lands of the arid region of the United States

Precipitation, 1971-2000

Copyright (c) 2006, PRISM Group, Oregon State University
http://www.prismlanduse.org - Map created Jun 16 2006
Thirteen River Forecast Centers
Established in the 1940s for water supply forecasting

Three primary missions:
1. Seasonal **Water supply forecasts** for water management
2. **Daily forecasts** for flood, recreation, water management
3. **Flash flood warning support**
Seasonal streamflow prediction is critical

One example:
Met. Water Dist. of S. California (MWD)

MWD gets:
1.25 MAF
OR
0.55 MAF
+$150M gap

from B. Hazencamp, MWD
How are forecasts created?
Water Supply Forecast Methods

- **Statistical Forecasting**
  - Statistical Regression Equations
  - Primary NOAA/National Weather Service forecast method from 1940’s to mid 1990’s.
  - Primary USDA forecast method, 1920s to present
  - Historical Relationships between streamflow, snow, & precipitation
  - Tied to a fixed snowmelt runoff periods (e.g., Apr-Jul)

- **Ensemble Streamflow Prediction (ESP)**
  - Relies on a continuous conceptual model (Sacramento-SMA & Snow17)
  - Continuous *real time* inputs (temperature, precipitation, forecasts)
  - 6-hour model input and output timesteps, run daily or weekly
  - Flexible run date, forecast period, forecast parameters.
  - ESP is primary forecast tool at NOAA now
Statistical Forecast Equations:

- Principle Components Regression (PCR)
- Predictor variables must make sense
- Challenge when few observation sites exist within river basin
- Challenge when measurement sites are relatively young
- Fall & Spring precipitation is frequently used (why?)

Sample Equation for April 1:
April-July volume Weber @ Oakley =
+ 3.50 * Apr 1st Smith & Morehouse (SMMU1) Snow Water Equivalent
+ 1.66 * Apr 1st Trial Lake (TRLU1) Snow Water Equivalent
+ 2.40 * Oct-Mar Chalk Creek #1 (CHCU1) Precipitation
- 28.27
USDA seasonal water supply forecast medians

Piedra River near Arboles (CO): Apr-Jul Volume

runoff forecast period

Hours of human effort

Raw daily statistical model

No human effort

Multi-agency consensus forecast

from T. Pagano

This is an automated product based solely on SNOTEL data, provisional data are subject to change. This product is a statistically based guidance forecast combining indices of snowpack and precipitation. Skill is defined as the correlation (squared) between the guidance and observed during calibration. This product does not consider climate information such as El Nino or short range weather forecasts, or a variety of other factors considered in the official forecasts. This product is not meant to replace or supersede the official forecasts produced in coordination with the National Weather Service. Science Contact: Jim.Marron@por.usda.gov www.wcc.nrcs.usda.gov/wsf/daily_forecasts.html

NRCS
Some water agencies go further than forecast agencies – use climate indices, or climate outlooks (i.e., from NWS Climate Prediction Center).
State agency statistical forecasts (based on climate indices)

Objective process allows hindcasting & verification
• Official ESP forecasts are based on
  • (1) initial model conditions (e.g. snow pack, base flow, etc)
  • (2) short-range weather forecasts (1-day, 3-day, 5-day, 10-day)
  • (3) ensemble of historical meteorological sequences
NWS River Forecast Process

Hydrologic Model Analysis
- Hydrologic expertise & judgment

River Forecast Modeling System
- Model guidance
- Parameters

River Forecasts
- Outputs
- Graphics

Decisions
- Rules, values, other factors, politics

Forecast precip / temp

Weather and Climate Forecasts

Analysis & Quality Control

Observed Data

Calibration
Observed forcings
Precipitation + Temperature 
  + Freezing level + ET
  • Process methods vary
  • Interactive Processes
  • Threshold and spatial comparisons
  • Systematic estimation
  • Manual forcing and over-rides
  • Hourly and max/min data (temperature)

Quality Control (QC) and processing procedures vary by region and RFC
Interactive methods
Output qualified for model use
National Center Support
Forecast Forcings

National Model Guidance available to WFO & RFC

WFO & RFC directly share gridded forecasts via GFE exchange

Grids at 4km or 2.5km

RFCs employ grid and point forcings to hydrologic model

Point or gridded data converted to mean areal forcings

WFO Weather Forecast Office

RFC River Forecast Center

GFE Gridded Forecast Editor

CHPS NOAA Community Hydrologic Prediction System
Runtime Modifications

- MOD capability has been available in the NWS >30 years
- Generic MOD capability implemented within FEWS
- Extend capability to other users outside of OHD-core models

Result: Improved observed period simulation

Hydrologist render a Run-Time modification to the SACSMA Model and increases the lower zone primary and supplemental states
Examples: Nooksack R

Typical situation during snowmelt: the simulation goes awry

- What can a hydrologist deduce from this simulation?
- As it is, blending simulation and obs gives an ‘unrealistic’ forecast
Examples: Nooksack R

One Solution -- Double the snowpack (WECHNG)

- Other approaches may also have been tried: lower temperatures, raise soil moisture, etc.
Examples: Nooksack R

The resulting simulation is better, hence the forecast is more confident.

- Flows stay elevated, have diurnal signal of continued melt.
Forecasts inform Water Management

CBRFC ensemble flow forecasts for Reclamation water management

Major reservoir management agencies are biggest users -- balance flood control with irrigation & supply needs, navigation, & environment

Graphic from Dr. Katrina Grantz, Bureau of Reclamation
Water supply forecasting

COLORADO - LAKE POWELL, GLEN CYN DAM, AT (GLDA3)
Water Year 2012, Forecast Period Apr-Jul (highlighted)

HISTORY (1981-2010):
- Period Minimum
- Period Normal
- Period Median
- Period Maximum

NORMALS:
- Monthly
- Period Sum
- Water Year Sum

OBSERVED:
- Monthly (QCMPBZZ)
- Water Year Sum

OFFICIAL FORECAST:
- Reasonable Maximum
- Final
- Reasonable Minimum
day-to-day changes in seasonal flow forecasts

- water managers / traders don’t like rapid changes in seasonal forecasts
  - at least, causes should be explicit

  **Water Supply Forecasts for JLKW4**

  - sudden changes can come from:
    - storm hits basin (rise in forecast) (clear)
    - change in short range weather forecasts (less clear)
    - forecaster modification to states (or auto-DA) (hidden)

- 1-day change in median ESP forecast (period Apr-Jul)
  - bars = no weather forecast (mostly state changes)
  - lines = 3 and 10 day weather forecasts included in ESP
day-to-day changes in seasonal flow forecasts

- embedding weather forecasts in seasonal predictions can improve skill
- BUT …. can also increase volatility -- especially if weather forecasts are not calibrated for skill (eg deterministic NWS)

1-day change in median ESP forecast (period Apr-July)
bars = no weather forecast (mostly see state changes)
lines = 3 and 10 day weather forecasts included in ESP

locations
Modeling & forecast methods can lead to systematic bias & spread errors
- met forecast ensemble may be uncalibrated
- ESP year/period selection can cause bias
- model predictand might not be well calibrated

*Post processing typically requires hindcasts*

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**Wood & Schaake, JHM, 2008**
In summary, both frameworks can be skillful

Yet both have drawbacks…

**NWS raw ESP**
- fails to account for hydrologic uncertainty
- may have bias and poor reliability
- tied to flood forecast process
  (desire for ‘seamless’ method)

**USDA statistical**
- confidence bounds inadequate
  (heteroskedastic error) in many places
- small samples for training (~30 yrs)
Recent developments in US
New US NWS system can incorporate climate forecasts

Hydrologic Ensemble Forecast Service (HEFS)
- now being deployed experimentally in some RFCs
- the climate forecasts are not very popular, versus the GEFS
- HEFS still harnessed to the manual flood forecast process (for warm states)

Demargne et al, 2014 BAMS
For seasonal time scales, skill varies from poor to moderate
  - depends on season and lead time

New systems, such as the North American Multi-Model Ensemble (NMME) may improve seasonal skill
  - 9 model ensemble in real time with hindcasts

East R at Almont, Co, precip
(very difficult location)
North American Multi-Model Ensemble at NOAA

- successful experimental phases leading toward operational production
- hindcasts should support skill-based combination and use

Used in new NWS HEFS system

Kirtman et al, 2014
North American Multi-Model Ensemble at NOAA

- models vary in skill each month, and by region
- current multi-model products just use ensemble mean
  - better combination approaches are possible
final comments
Main options for seasonal streamflow forecasting

**Dynamical-statistical (model-centric)**
- Hindcasted!
- Objective DA or none!
- Warm hydrology model(s) states
- Future model(s) states & fluxes
- Statistical calibration post-processing model merging climate weighting

**Statistical**
- Hindcasted for predictive uncertainty (not just trained)
- In-situ obs climate/land indices/states*
- Statistical model(s)

* past obs/indices/states for training & hindcasts; current/future for prediction
** could be from model(s)

* Dynamical model approaches are popular now, but operational statistical forecasting systems tend to be **more complete**
  *X = often missing elements*
How to avoid version 1 becoming a legacy?

In the US, the two main seasonal streamflow forecasting approaches were created **over 35-years ago**, and have barely evolved since.

- ESP, statistical forecasting via regression
  - little to no use of climate forecasts in forecasting agencies
  - some operational datasets have not been updated in 20 years

**Challenge** – to create an operational forecasting process that allows a steady influx over time of new science, data, technology, and thinking

- more important than the details of the approach taken to start

**The operational framework needs elements that support innovation, eg:**

- a developmental testbed that involves forecasters
- use of operational benchmarking and verification
- a repeatable process that can support experimentation and evaluation
- incentives for operational fiefdoms to evolve
  (main incentive cannot be simply operational regularity)
- flexible, adaptable, extensible operational software and platforms
  (consider a cell phone company, for comparison)
- other suggestions?
Questions?

andywood@ucar.edu

http://en.wikipedia.org/wiki/Lake_Powell
extra slides
NWS - manual, subjective process

**Process**

- Meteorological analysis
- WFO+HPC met. forecast
- Hydrologic simulation and flood forecasting
- Long-lead forecasting
- Coordination with other agencies

**Manual elements**

- Quality control of station data
- Quality control of radar and radar parameters
- WFO forecast itself (though based on models)
- RFC merge with HPC forecast (similar to WFO)
- Sac./Snow17 model states and parameters
- Bias-adjustment relative to obs. Flow Input forcings (2nd chance at adjustment)
- Model states as adjusted for flood forecasting
- Choice of models (statistical / ESP)
- Blend of models
- Choice of meteorology: QPF, ENSO, None?
- Merging with NRCS statistical forecasts means, confidence limits (“10-90s”)
Atmospheric Pre-Processor: calibration

Off line, model joint distribution between single-valued forecast and verifying observation for each lead time

Archive of observed-forecast pairs

Joint distribution
Sample Space

Observed

Forecast

NQT: Normal Quantile Transform

Schaake et al. (2007), Wu et al. (2011)
Atmospheric Pre-Processor: ensemble generation (1)

In real-time, given single-valued forecast, generate ensemble traces from the conditional distribution for each lead time.

Given single-valued forecast, obtain conditional distribution.

Schaake et al. (2007), Wu et al. (2011)
Opportunities for prediction

**hydrological predictability**

- How well can we estimate the amount of water stored?
  - Accuracy in precipitation estimates
  - Fidelity of hydro model simulations
  - Effectiveness of hydrologic data assimilation methods

**meteorological predictability**

- How well can we forecast the weather?

**Opportunities:** Which area has most potential for different applications?
Hydroclimate/Seasonal Variation in Predictability Source

- humid basin
- uniform rainfall
- no snow
- small cycle driven by ET

- cold basin
- drier summers
- deep snow
- large seasonal cycle
- April snowmelt dominates May-June runoff
Assessing the sources of flow forecast skill
vary predictor uncertainty → measure streamflow forecast uncertainty

http://www.ral.ucar.edu/staff/wood/weights/  
Wood et al, JHM 2014 (submitted)
Flow Forecast Skill Sensitivities

A Rain-Driven Basin

- IC skill matters most for 1 month forecasts
- For longer forecasts, met forecast skill dominates

Assuming no skill in one source (model accuracy for watershed states, or forecasts)…what are the benefits of adding skill in the other source?

Results are preliminary and subject to change
A Snowmelt Basin

- Wide seasonal variations in influence of different skill sources
- Cold/Warm and Dry/Wet patterns are clear
- Skill increases in meteorology produce non-linear skill changes in flow

Assuming no skill in one source (model accuracy for watershed states, or forecasts)…what are the benefits of adding skill in the other source?

Results are preliminary and subject to change
Snow-Driven Basin in the Western US

- Wide seasonal variations in influence of different skill sources
- Cold forecast period (Jan-Mar) -- forecast skill depends mainly on initial condition accuracy
- Warmer snowmelt forecast period forecast skill depends strongly on met. forecast skill

IHC: initial Hydrologic Conditions
SDF: Seasonal Climate Forecasts
Flow Forecast Skill Elasticities

- The % change in flow forecast skill versus per % change in predictor source skill
- Can help estimate the benefits of effort to improve forecasts in each area
Assessing regional variations

Regional Streamflow Forecast Skill Dependence
1 month Mean Flow

Elasticity (% flow fcst skill / % predictor skill) versus Forecast Init. Month

Results are preliminary and subject to change

- Based on ~420 watersheds, 30 year hindcasts
Assessing regional variations

Regional Streamflow Forecast Skill Dependence
3 month Mean Flow

Elasticity (% flow fcst skill / % predictor skill) versus Forecast Init. Month

Results are preliminary and subject to change

- Based on ~420 watersheds, 30 year hindcasts
Assessing regional variations

Regional Streamflow Forecast Skill Dependence
6 month Mean Flow

Elasticity (% flow fcst skill / % predictor skill) versus Forecast Init. Month

Results are preliminary and subject to change

- Based on ~420 watersheds, 30 year hindcasts