Log-Exponential Reservoir Operating Rules for Global and Regional Hydrological Modeling

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University of New Hampshire

Water Systems Analysis Group

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NEW HAMPSHIRE EPSCoR

Reservoir Operating Rules→ Modeling (Water Balance, Routing) → Interpretation and Analysis

Abstract

Many hydrological models simulate both runoff (Water Balance Model) and discharge (Water Routing) over given river networks (STN, DRT, HydroSHEDS, etc.). But water infrastructure development (dams, inter-basin water transfer lines, irrigation canal networks, etc.) in industrial and post-industrial time frames impose real challenges to the modeling of water routing and prediction of river discharge, especially for large-scale regional and global geographic extents where detailed information about operating rules for such hydro-infrastructure units often do not exist. The global and regional river dam databases used in water routing simulations (e.g. GRanD and NID) provide some limited information on dam construction dates and purposes (e.g. hydropower, irrigation, water supply, flood control, etc.), but do not indicate how these are being operated over the given hydrological year cycle and over extreme low/high in-flow regimes. So the formulation of generic and use-specific reservoir operating rules for regional and global hydrologic simulations are still debated issues for the hydrology modeling community.

In our network independent WBM-TrANS model (Water Balance Model-Transport from Anthropogenic and Natural Systems) we have formulated and tested a new Log-Exponential OPerAting Rule for Dams (LEOpaRD) that can be readily parameterized for a generic and/or specific dam purpose. The key features of the LEOpaRD formulation include a combination of adjustable logarithmic and exponential functions describing the release of water from the reservoirs and other adjustable parameters for minimum storage and two exponent curvature coefficients (one each for logarithmic and exponential functions). In the LEOpaRD model the dam discharge/release calculations are normalized to Average Annual Discharge (AAD), which, in turn, is taken as a running average of the past 5 years. The latter is critical to simulate dam fill-up periods and shifts in the hydrological cycle over long-term climate variability (e.g. climate change and direct human modification).

Here we present testing of the LEOpaRD rules in both regional and global model runs. Results indicate a very good match of observed vs. modeled reservoir release flows for a number of large, medium, and small relative-capacity dams. We also found that LEOpaRD produces satisfactory results for dam fill-up periods following construction, which can take several years for large dams. Dam removal flow can also be simulated by linear reduction of reservoir capacity to zero over the residence time of the reservoir.

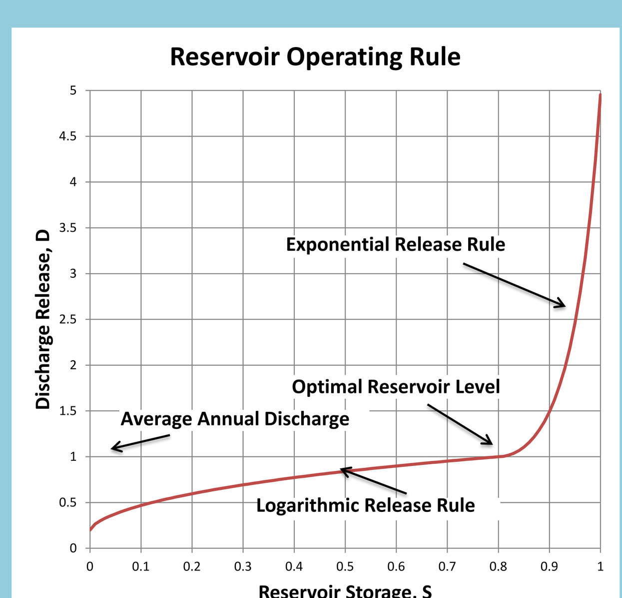
Reservoir Operating Rule

Reservoir release is a function of reservoir storage level. The rule consists of two segments-

1. Rule at reservoir storage below optimal level (e.g. 80 % full) - Logarithmic behavior.
2. Rule at reservoir storage above optimal level (e.g. 80 % full) - Exponential behavior.

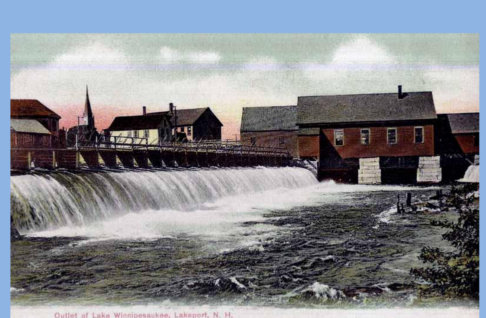
The rule is based on two characteristic points and five parameters-

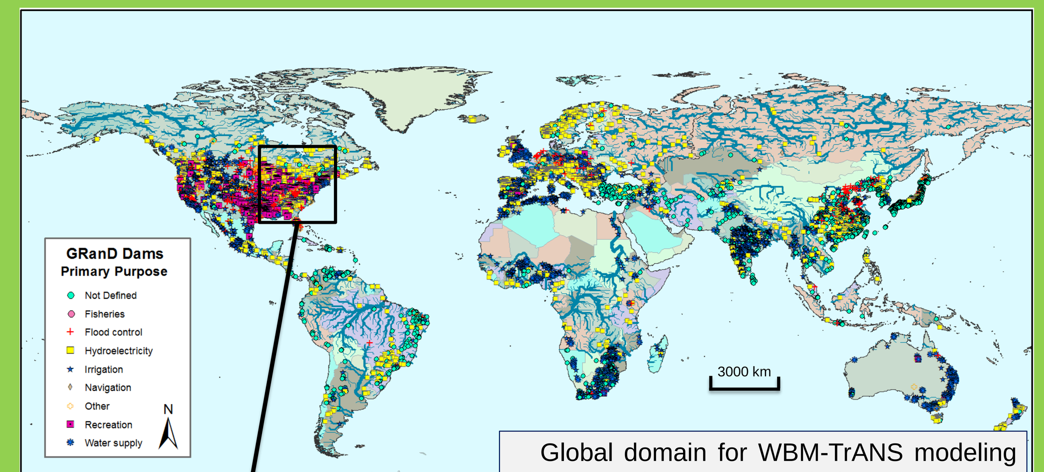
1. Optimal level of reservoir storage (80 % full). When reservoir is at its optimal level the reservoir release is equal to average annual discharge.
2. Minimum allowed reservoir release (20 % of average annual discharge).
3. Average annual discharge is calculated over past 5 full years (the present year is not accounted as being partial year).
4. Discharge to Capacity ratio (Regulatory capacity- see below).

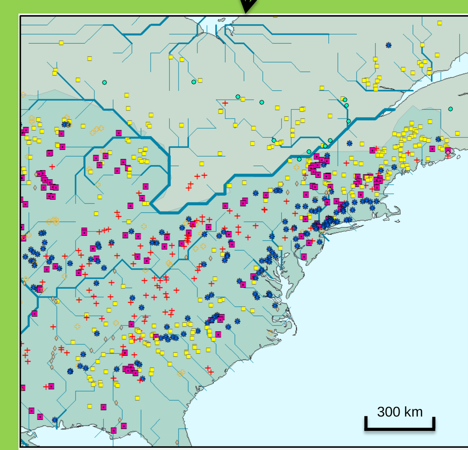


$$\begin{cases} D = D_{min}S_R + ln\left(kS^{\alpha/\sqrt{S_R}} + 1\right) & at\ S < S_{Optimal} \\ D = exp\left(b\left(S - S_{Optimal}\right)^2\right) & at\ S \geq S_{Optimal} \end{cases} \qquad (1)$$

where $k = \frac{1}{S_{Optimal}{}^{\alpha/\sqrt{S_R}}}[exp(1 - D_{min}S_R) - 1]$, b = 10, α = 2/3, and 0.1<S_R<1 is regulatory capacity. S_R is a ratio between annual cumulative flow volume and the reservoir capacity.



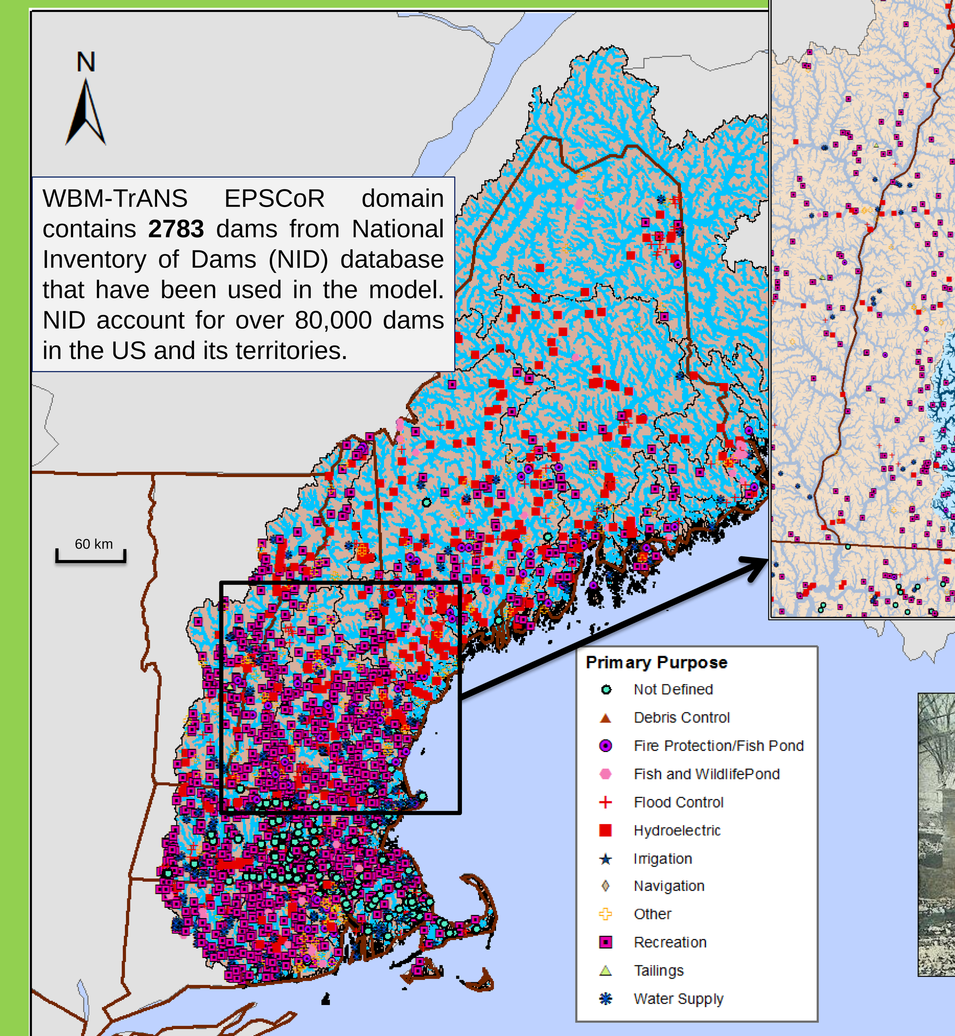




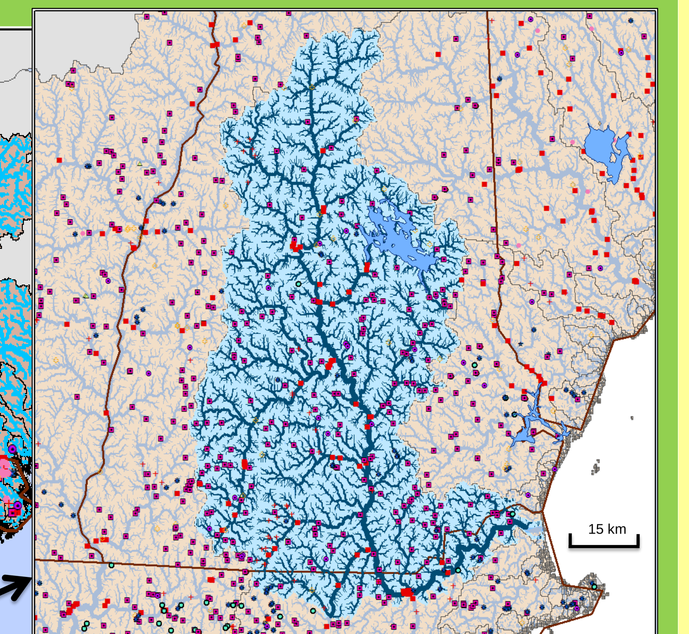
Global domain for WBM-TrANS modeling with **6882** dams from Global Reservoir and Dams (GRanD) database that have been used in the model.

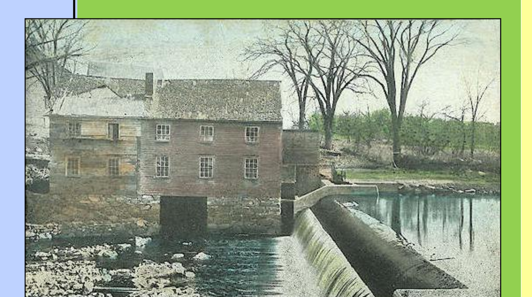
Lehner, B., Liermann C., et al. (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and Environment 9(9): 494-502.

Hoover Dam, Nevada/Arizona border



WBM-TrANS EPSCoR domain contains **2783** dams from National Inventory of Dams (NID) database that have been used in the model. NID account for over 80,000 dams in the US and its territories.



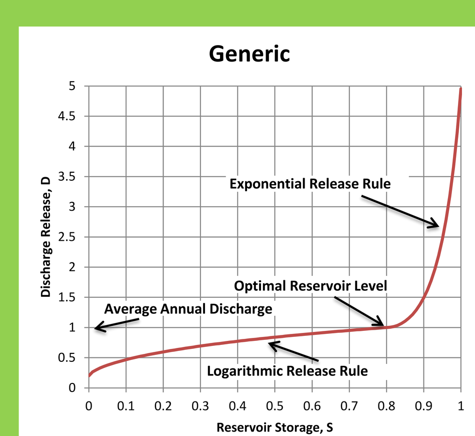


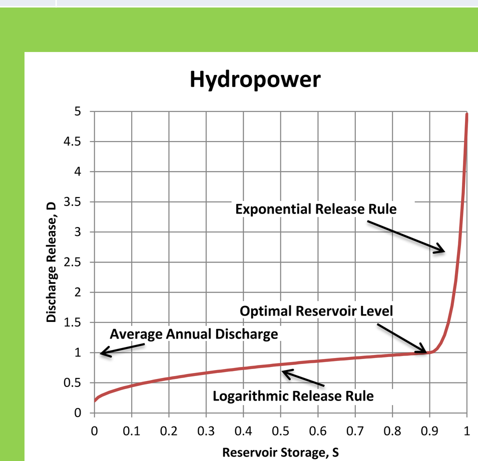
Old Mill & Dam, Durham, NH

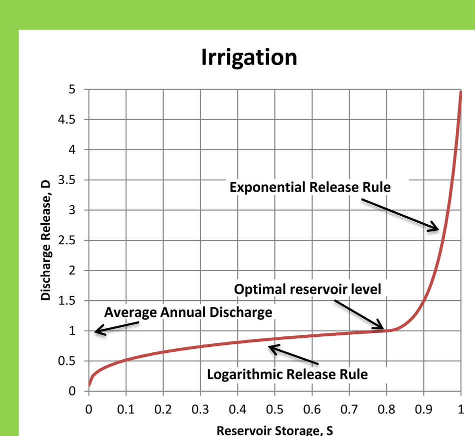
Parameterization, Based on the Dam Use

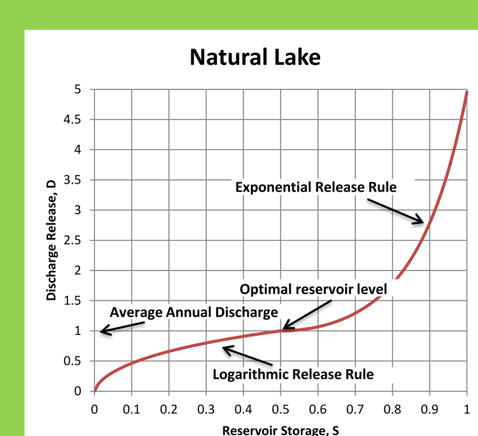
Table of suggested parameters for Equation (1)

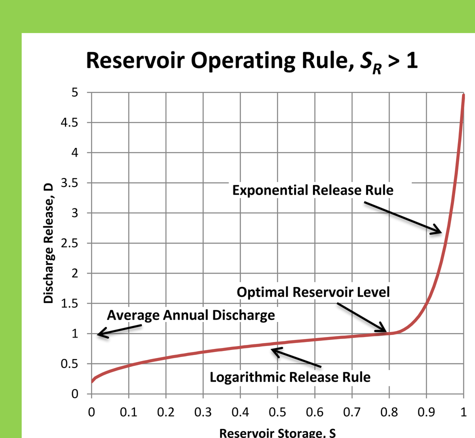
Dam Purpose	$\overline{D}_{min}$	$S_{Optimal}$	b	α	Comment
Generic	0.2	0.8	10	2/3	Works for most of dams
Hydropower	0.2	0.9	40	1	Steeper curve to keep high water level
Irrigation	0.1	0.8	10	1/2	Flatter curve to have more even discharge
Natural Lake	0.0	0.5	1.6	2/3	Smooth curve, release is smoothed inflow

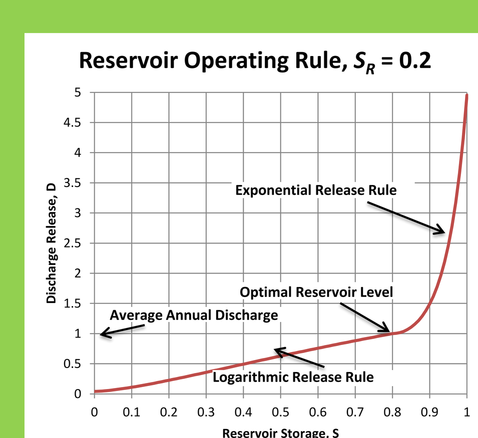






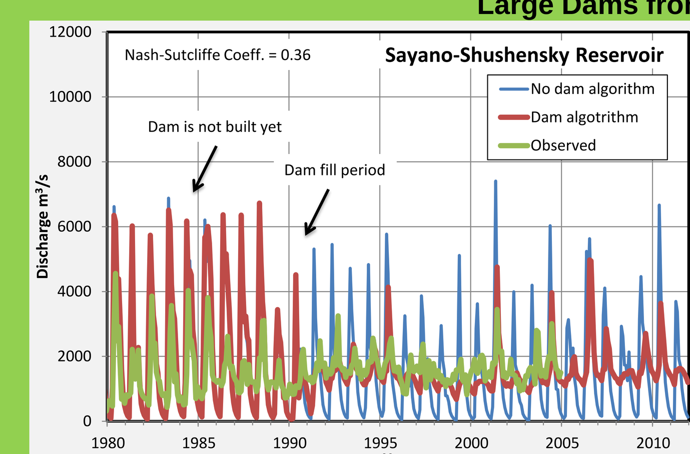


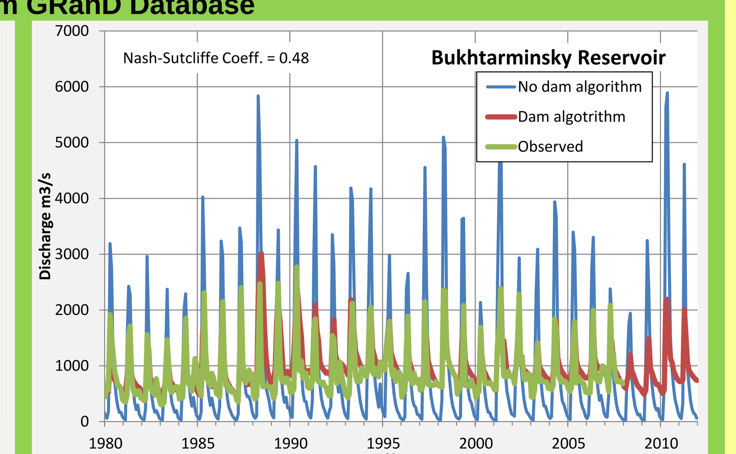


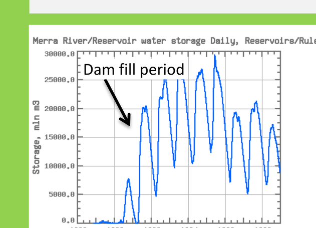


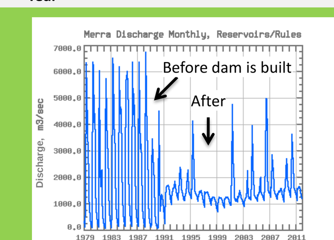
Simulated and Observed Discharge

Large Dams from GRanD Database





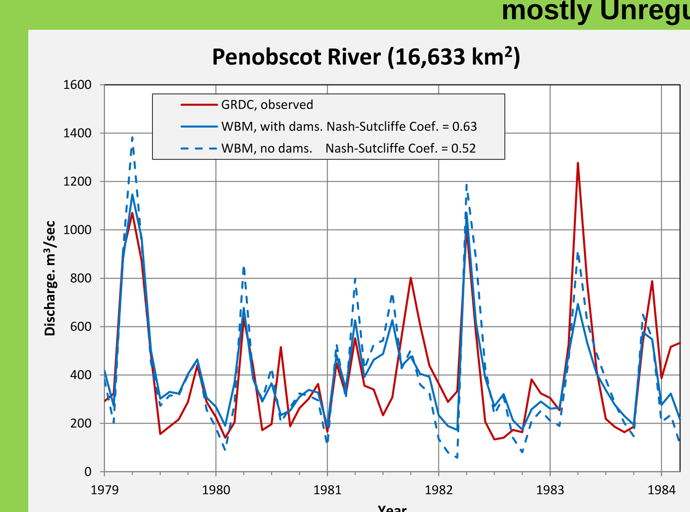


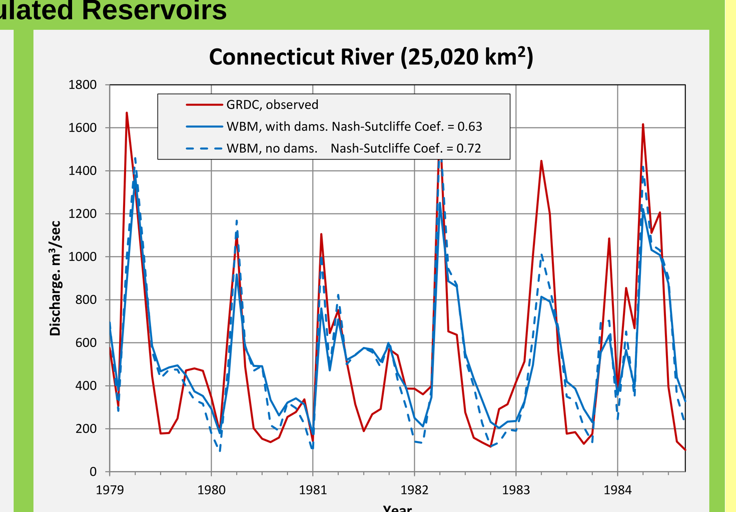


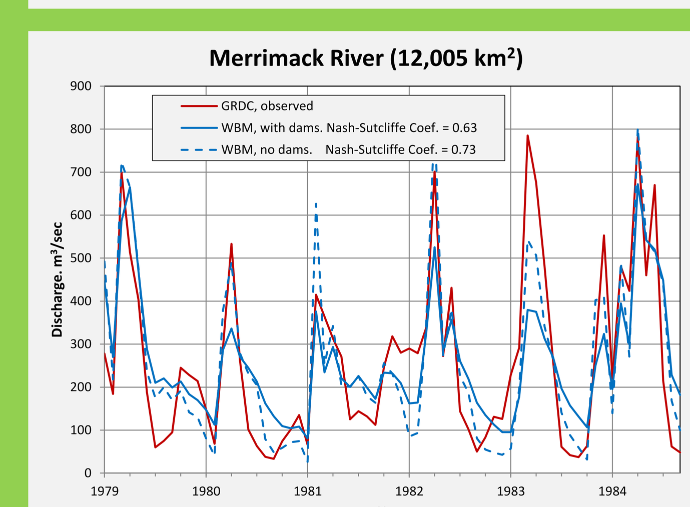
Large volume dams are always regulated to maintain an optimal water release rate that ideally must be an annual average flow (**graphs on the left**).

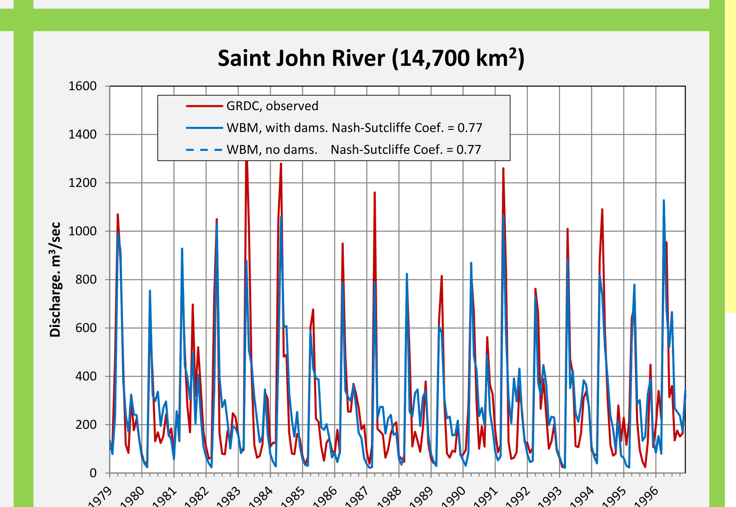
A spike release occurs when reservoir storage exceeds 80 % of its capacity. Frequency of spike releases is a function of *regulatory capacity (RC)*. Reservoirs with small RC have a spike release almost year (**graph above**).

Small Dams from EPSCoR Domain- mostly Unregulated Reservoirs









Water Balance and River Routing Model (WBM)

Basic features:

- Physically based 2-layers hydrological model with daily time step;
- Several approaches for evapotranspiration evaluation;
- Transport of surface runoff downstream using simulated river network (STN) and (1) Linear Reservoir or (2) Muskingum-Cunge flow routing model;
- Tracking of water components by origin, use, and chemistry;
- Human disturbances: irrigation, reservoir regulation, inter-basin water transfer.

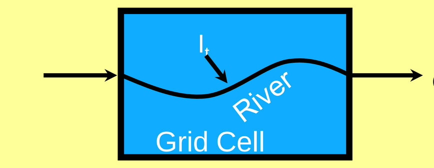
Flow routing model

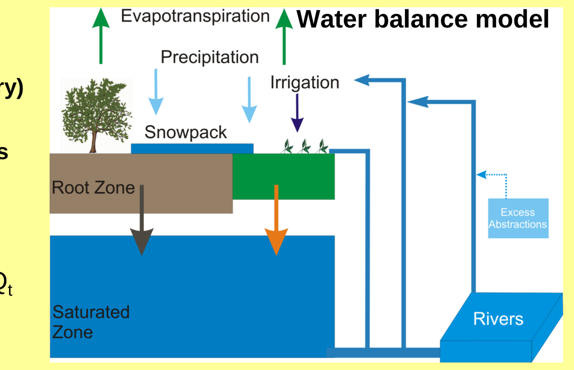
$Q_{t+1} = C_0 I_{t+1} + C_1 I_t + C_2 Q_t$

Coefficients C_0, C_1, C_2, = f(River Geometry)

Q = river discharge from grid cell

I = locally generated inflow to river (less irrigation)





Discussion and Conclusions

Advantages of the new Log-Exponential OPerAting Rule for Dams (LEOpaRD) vs. traditional approaches are-

- Simple parameterization that requires small number of variables to work.
- Same generic rule can be applied to different purpose reservoirs (hydroelectricity, irrigation, etc.) through just four adjustable (by calibration) parameters.
- Can be easily incorporated into Global or regional WBM/WTM framework since it requires just two water routing variables- (a) current (time series) inflow (discharge) rate, and (b) 5-year running average inflow (discharge) rate.
- LEOpaRD adapts to climate (runoff) variability/change in case of long time series simulations (50+ years) by using 5-year running average parameterization. So, it can be used for IPCC AR4/5 climate drivers for hydrology regime modeling.
- The new algorithm works with Global (GRanD) and regional (NID) dam databases.
- Reservoir fill-up (after construction is completed) is reasonably well simulated without change of basic parameters specific to its purpose (hydroelectricity, etc.).
- Accounts for water evaporation/loss from the surface of the reservoir.

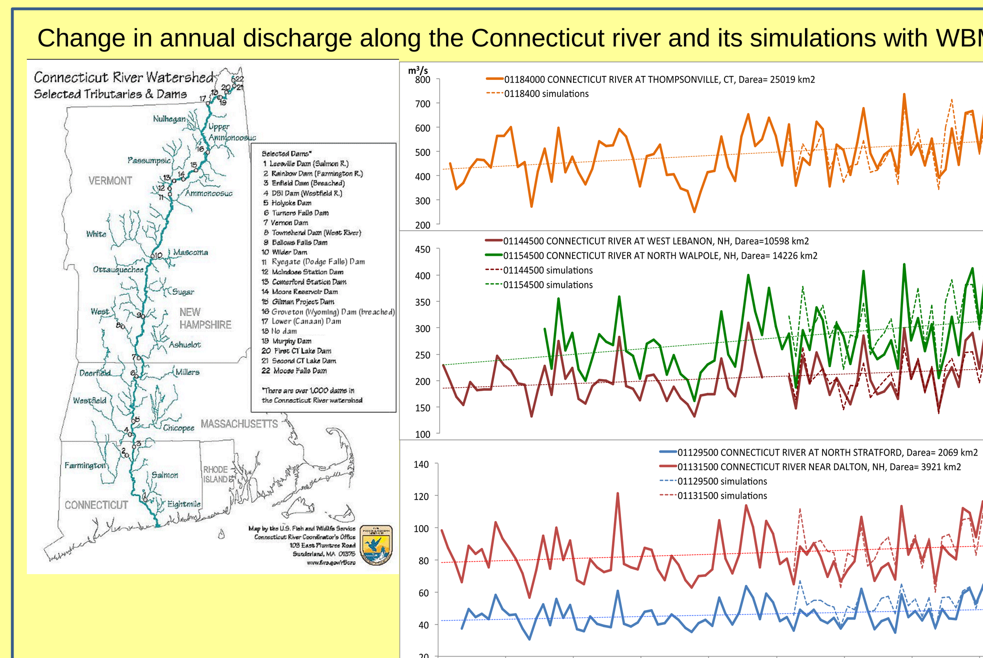
Disadvantages (or problems to overcome in subsequent research) of the Log-Exponential rules are-

- LEOpaRD works better for large capacity dams where outflow regime is regulated daily by dam operating staff. But it performs poorly for uncontrollable spillover small dams which usually have low regulating capacity. Database (mostly NID) tags on small reservoir purposes are forcing the LEOpaRD to apply specific dam purpose parameters while it would do better by overwriting those with "lake" rule/purpose parameters (see Table of this poster).
- A response to downstream water demand is not built in yet. It is mostly important for irrigation and water supply purpose reservoirs.
- Does not account for water seepage/loss to groundwater pool which makes virtual reservoir by-pass from upstream to downstream flow.

This work is still in progress as part of WBM_TrANS development efforts led by International team of co-authors.

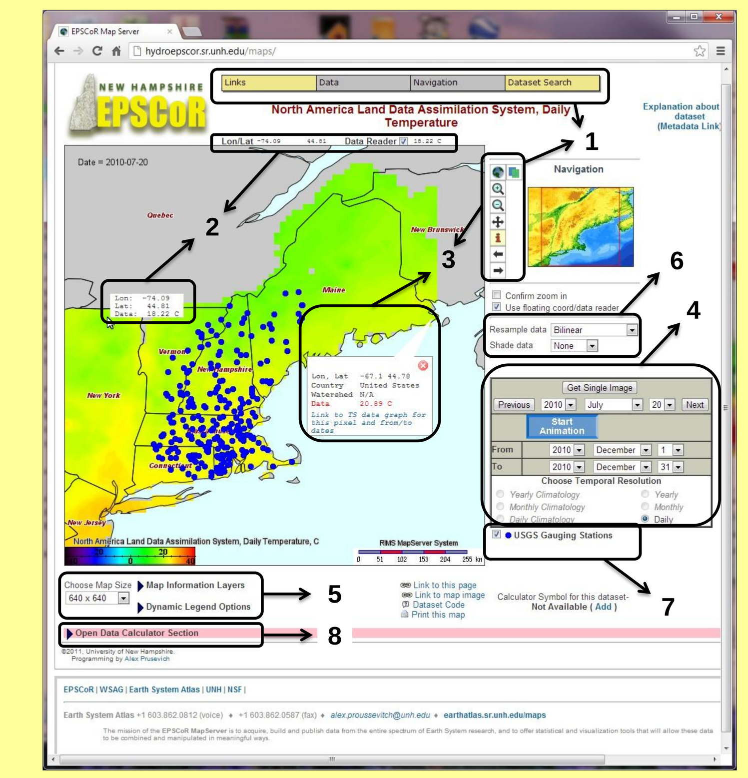
Climate Change and Shifts in 5-Year Average Runoff Affects Reservoir Modeling

Change in annual discharge along the Connecticut river and its simulations with WBM



There is a significant positive trend (p < 0.05) in annual discharge for all gauges on Connecticut river. WBM discharge simulations with MERRA input data show good correspondence with observations (R>0.74) in spite of numerous dams (see the map).

Web Client Application for EPSCoR Modeling Framework (RIMS Prototype)



1. Data search/selection, spatial navigation, metadata link, etc.;
2. Coordinate and map data value reader;
3. Pixel query tool (i-tool) gets coordinates, country, watershed, and map data value;
4. Time series navigation tool;
5. Map size, base layer, dynamic legend choices;
6. Data interpolation and shading tools;
7. Point/station data list with clickable symbols that open station pages in a separate browser window;
8. Fold-out section to run the Data Calculator application to perform mathematical and logical functions over gridded or vector datasets;

Links to Land Hydro-Biochemistry-Ecoservices (LHBE) system for EPSCoR

1. Data Query, Visualization, and Analysis Tool (Hydro-EPSCoR)- http://hydro-epscor.unh.edu/maps/
2. Data Query, Visualization, and Analysis Tool (Global)- http://earthatlas.sr.unh.edu/maps/
3. WBM validation Tool (Hydro-EPSCoR and Global)- http://earthatlas.sr.unh.edu/wbm_validation/MODEL_ID/
4. PnET (photosynthesis, net primary production model)- http://www.pnet.sr.unh.edu/
5. DNDC (DeNitrification-DeComposition Model)- http://www.dndc.sr.unh.edu/ http://nugget.sr.unh.edu/ http://earthatlas.sr.unh.edu/dndc/dndcClimateMap.html http://earthatlas.sr.unh.edu/dndc/dndcDairyMap.html
6. Human impact on fresh water hydrology- http://www.riverthreat.net/
7. UNH Water Systems Analysis Groups (WSAG)- http://www.wsag.sr.unh.edu/
8. USGS gaging station network- http://waterdata.usgs.gov/nwis/sw

Acknowledgements

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