Melt and Flooding in the Himalayan River Basins

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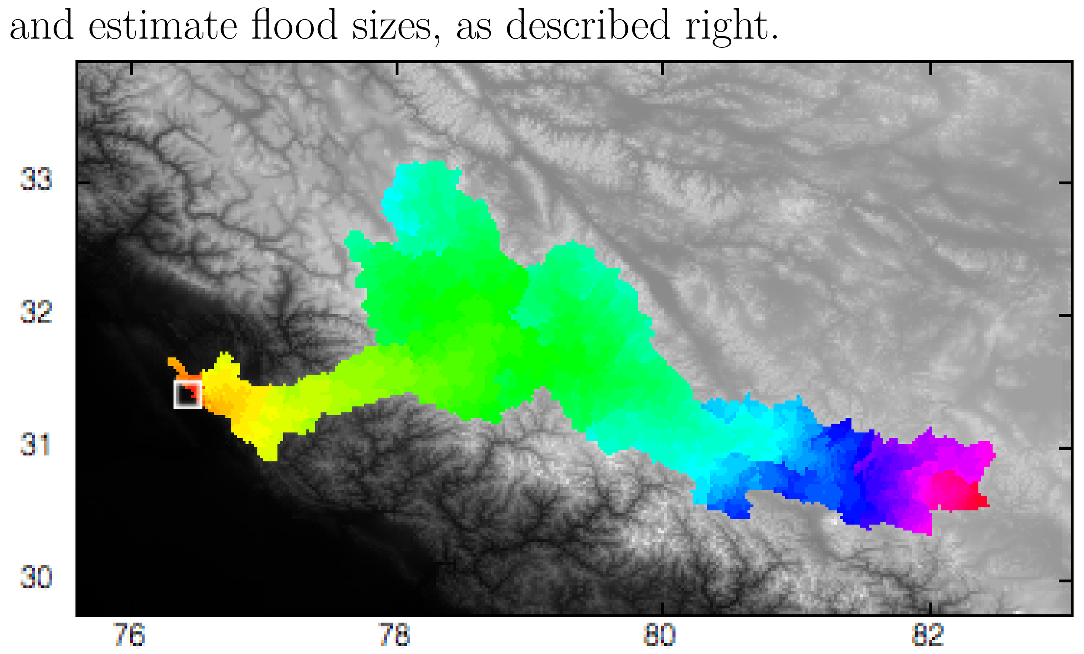
Research Question

Snow and ice melt form significant contributions to river base flows throughout the Himalayas, but their contribution to seasonal and catastrophic flooding is unclear. As glaciers melt and winter accumulation and temperature patterns shift with climate change, this contribution will cause changes to flood risk. This research combines remote sensing data with flow data from the Bhakra Dam to estimate past melt contributions and changes in future flood risk.

The Bhakra Dam

The Bhakra Dam on the Satluj River, a tributary of the Indus, has previously been analyzed for its monthly streamflow from melt [1] and flow predictability [2]. Here, daily inflow measurements from the dam are used to calibrate a custom flow model and estimate flood sizes, as described right.



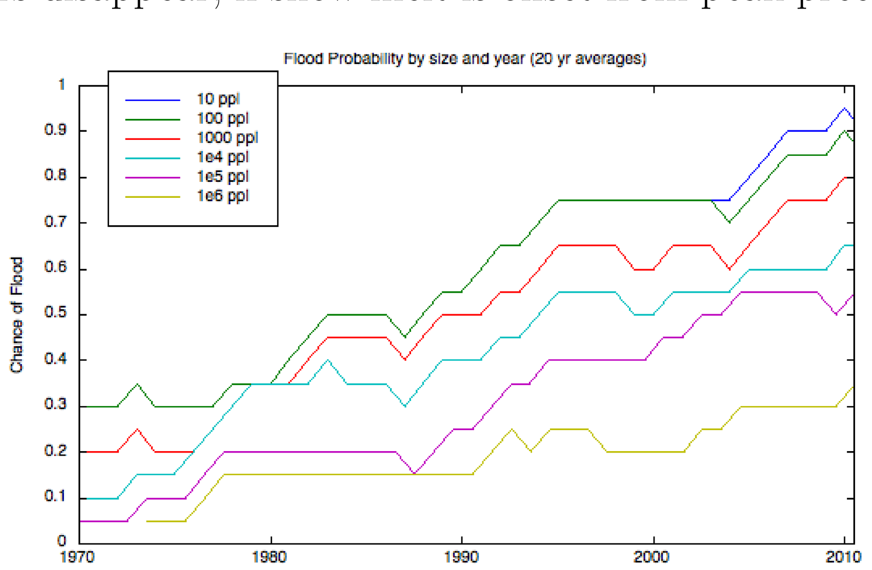
Bhakra dam basin (white box). Colors show relative travel times for runoff.

Main Results

- The size of the 10-year flood is 9 - 17% attributable to melt at the Bhakra Dam, and 5 - 10% in the Himalayan rivers, but is highly spatially heterogeneous.
- Variability in temperature contributes very little to the flood size (∼.03%).
- In the absence of accumulation changes, for each degree C of climate warming, the melt percentage increases by 1%.

Implications

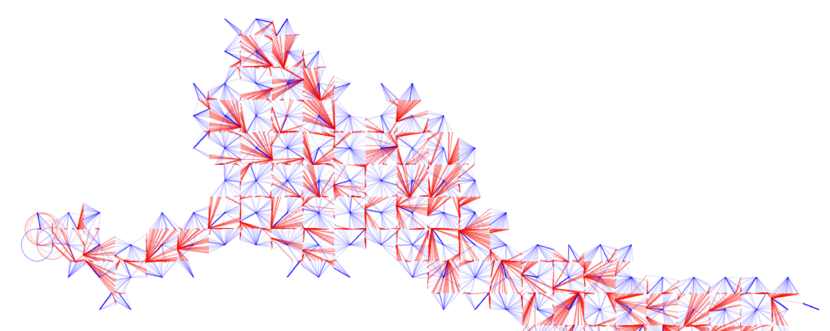
Flooding is becoming an increasingly pressing issue (see graph below). This study suggest that floods will increase 2.5% with a 2°C increase in temperatures, then decrease by up to 17% as glaciers disappear, if snow melt is offset from peak precipitation.



20-year averages of people affected by flooding in Pakistan, from the EM-DAT database.

Methodology

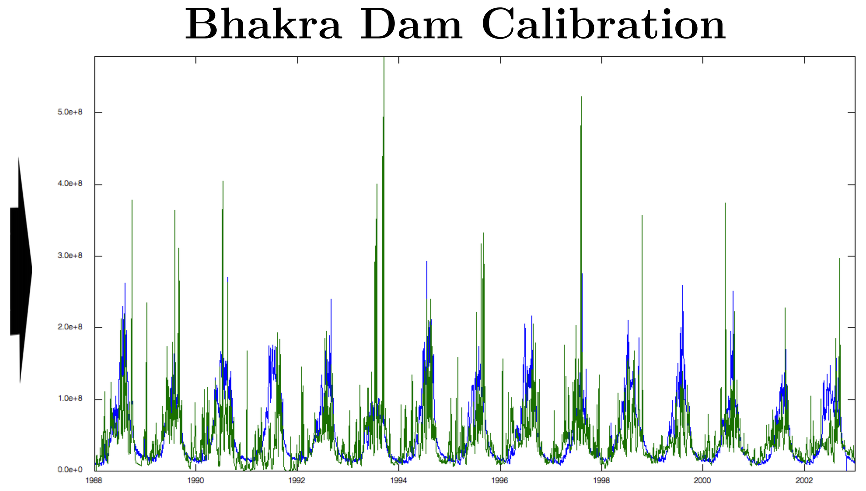
Network Flow Model



Flow paths, .25° resolution based on .0083° resolution D∞ directions. Blue for surface flows, red for rivers.

Basin flow modeled with a runoff network, tracking separately precipitation and melt flow. Melt estimated by calibrated temperature coefficients.

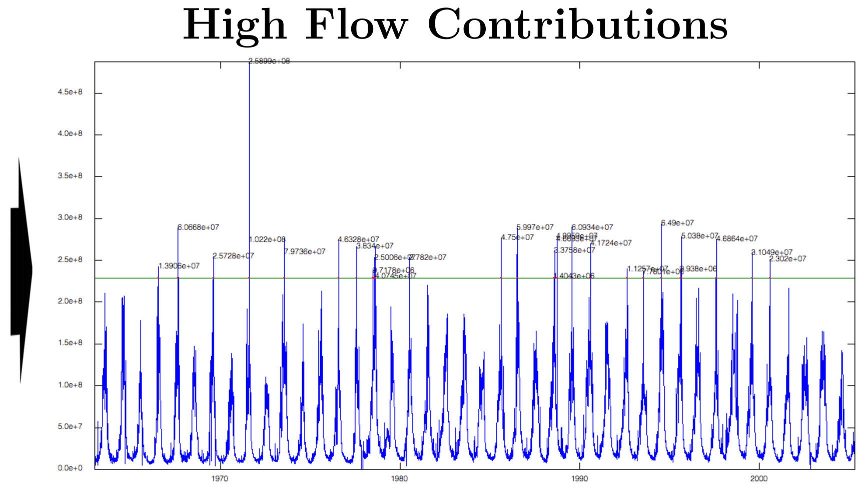
Bhakra Dam Calibration



Modeled melt and precipitation flow, combined (green), and measured Bhakra inflows (blue).

Model calibrated on daily Bhakra Dam inflow rate and remote sensing data, from 1988 - 2002 (the range of the snow/ice cover data).

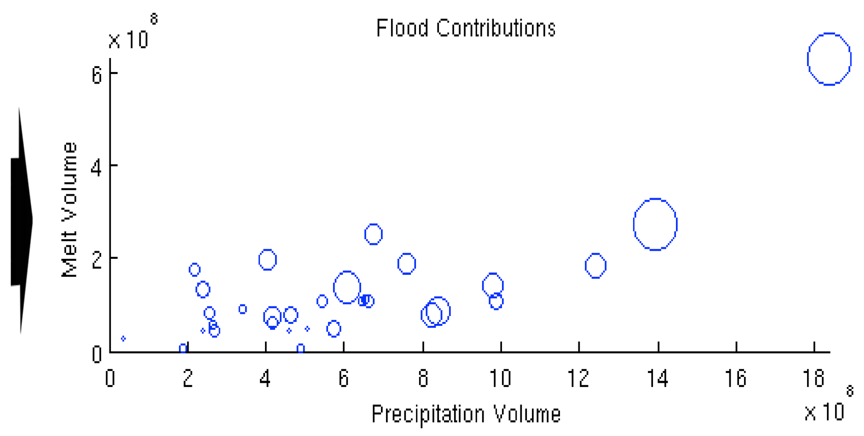
High Flow Contributions



Measured floods, shown with volumes (in m^3), at the Bhakra dam.

Floods quantified as "volume over banks" (medium year max flow). These are compared to the combined precipitation and melt flow estimated by the model.

Probability Model



Flood pdf estimation data points; sizes of circles show relative flood size.

Flood data used to fit a copula-based joint probability distribution. The univariate pdfs were estimated using a log-normal kernel, to capture the extreme values.

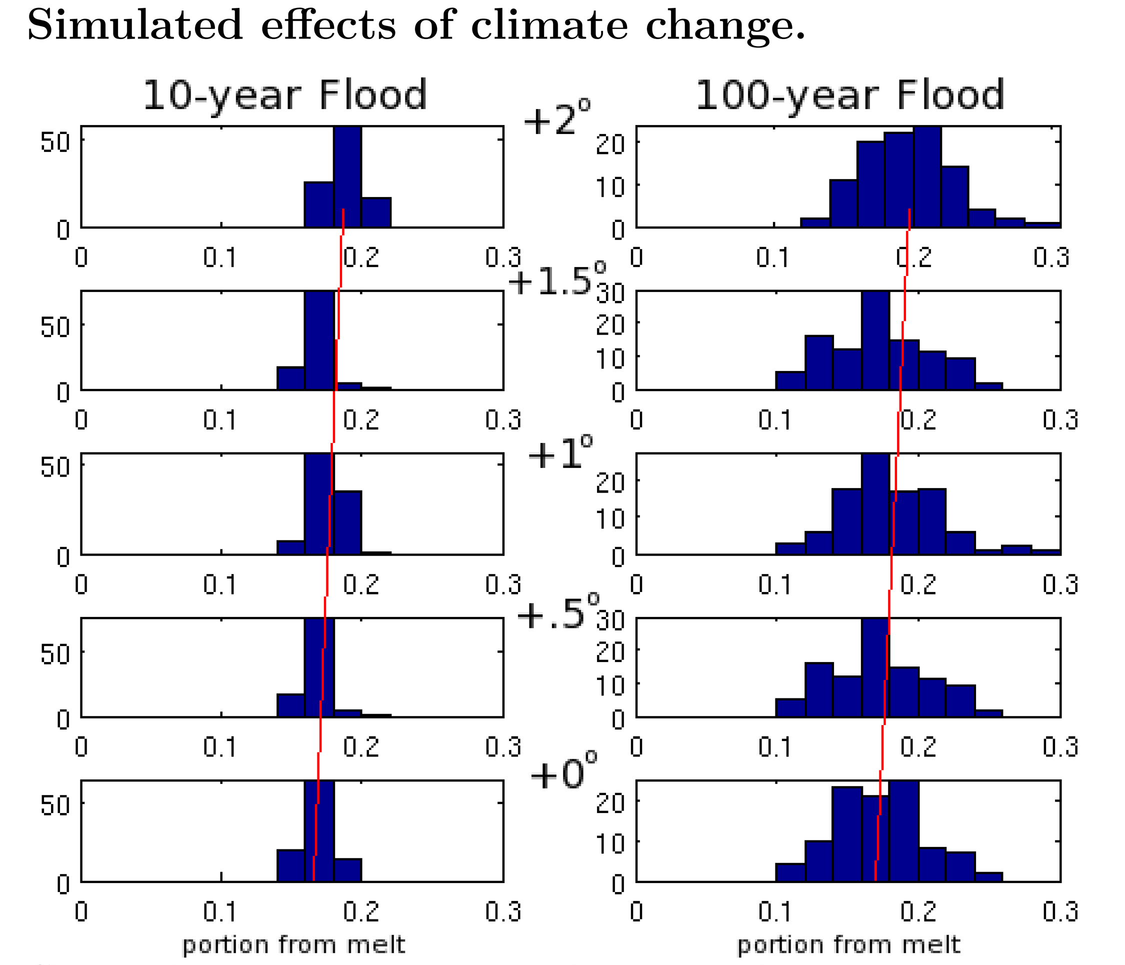
Bhakra Dam Results

Estimated contributions to floods from melt, under various models.

Model	10-year	100-year
1. **region sums, OLS calibrated**	8.97%	5.74%
2. **sums with melt variability**	9.00%	5.76%
3. **lnorm kernel, Gaussian copula**	17.02%	17.37%
95% confidence	±.002	±.006

Model 1 totals the precipitation and melt flows for regions based on their typical travel times to the dam, and scales these to match the measured flows with an OLS regression. Model 2 considers the additional effect of variability in temperatures (see Isolating Variability box). Model 3 uses the process described above.

Simulated effects of climate change.



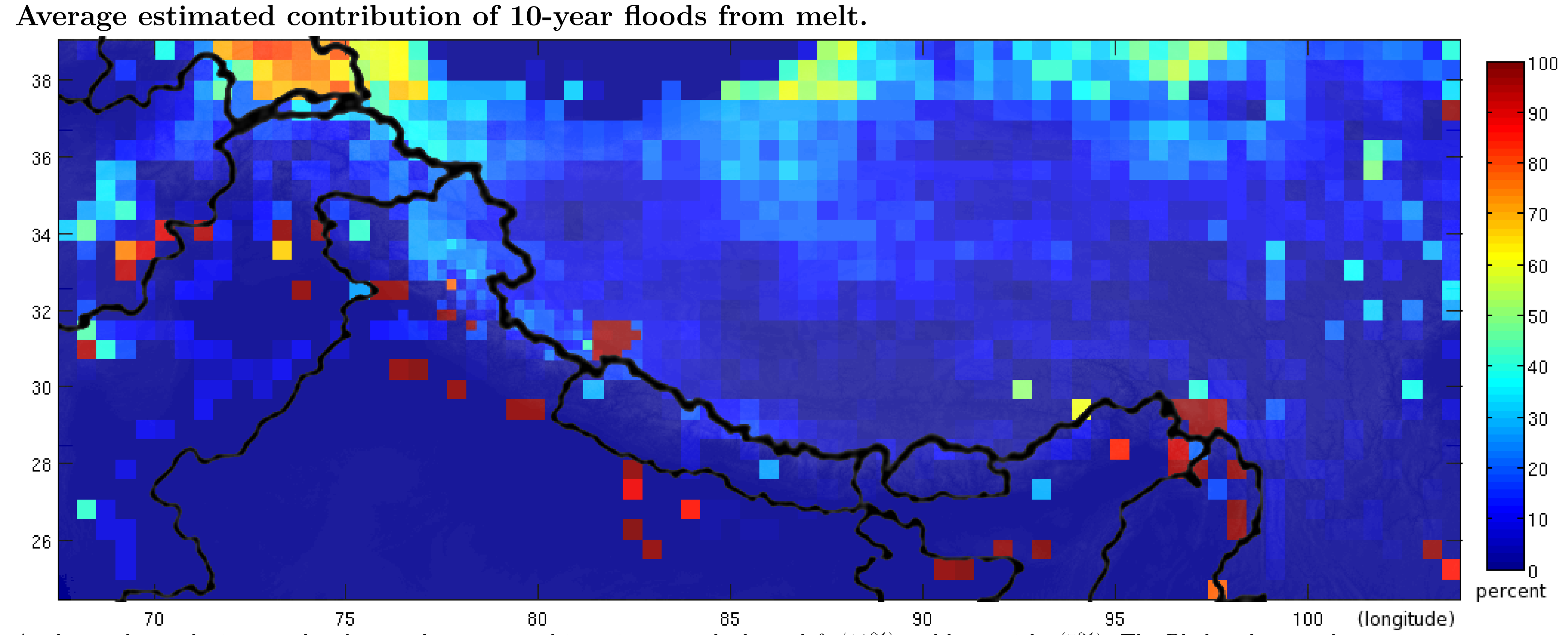
Climate change simulations using only constant changes in temperature. This is not a realistic simulation, and the increasing melt portions are a necessary result, but in the absence of reliable precipitation change predictions, this helps estimate the general trend (red line)

Climate change regression model: $P_i = \beta_0 + \beta_1 \Delta T_i + \epsilon_i$.
P_i: sample portion of flood from melt.
ΔT_i sample difference in temperature.

Coefficients	constant	ΔT	(R^2)
10-year	.1660	.0104	(.319)
100-year	.1698	.0119	(.065)

Full Himalayan Results

Average estimated contribution of 10-year floods from melt.



As shown above, the increased melt contribution extend into rivers, on the lower left (10%) and lower right (5%). The Bhakra dam catchment is provided in higher resolution, reflecting both the closer applicability of the calibrated model, and the detailed remote sensing data available for that region. Some individual pixels are shown as having very high melt contributions; these may be due to flow path errors.

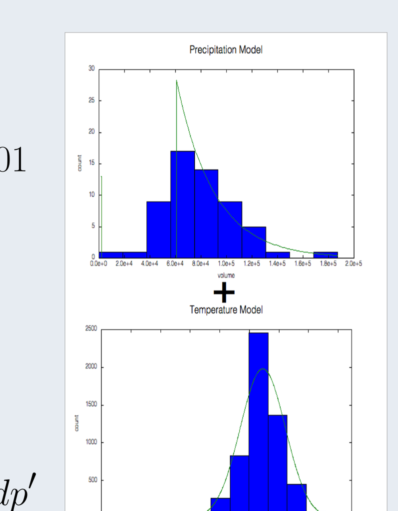
Isolating Variability

Probability models were estimated separately for precipitation and melt (with weekly temperature variation), by maximum likelihood. For an Gaussian temperature and exponential tail for precipitation, these can be analytically combined.

For a constant melt of $A\bar{T}$, the size of a 100-year flood is,

$$P(\bar{Q} \geq q) = \int_q^\infty \frac{(1-\alpha)}{\rho} e^{-\frac{p' - p_0 - A\bar{T}}{\rho}} dp' = .01$$

$$\implies q = p_0 + A\bar{T} - \rho ln(\frac{.01}{1-\alpha})$$



For melt following a normal distribution with μ and σ,

$$P(\bar{Q} \geq q) = \int_q^\infty \frac{(1-\alpha)}{\rho} e^{-\frac{p' - p_0}{\rho}} \star n(\mu, \sigma^2) dp'$$

$$\implies q = p_0 - \rho ln(\frac{.01}{1-\alpha}) - \frac{\rho}{2\sigma^2}[(\frac{\sigma^2}{\rho} + \mu)^2 - \mu^2]$$

References

[1] Singh, Pratap, and SK Jain, 2002. Hydrological Sciences Journal 47 (1): 93 - 106.

[2] Pal, I. et al (in press). Predictability of Western Himalayan River Flow: Melt Seasonal Inflow into Bhakra Reservoir in Northern India.

Data: Bhakra inflows from the Bhakra Beas Management Board of India. DEM from GLOBE (NOAA, The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model, Version 1.0, 1999). Weekly snow from NOAA NCDC (SSM/I, .333°x.333°). Daily precipitation from NASA TRMM (TRMM_3B42 v6, .25°x.25°), the India Meteorological Department (NCC1-2008, 1°x1°, and RF0p5, .5°x.5°), and the NOAA NCEP/NCAR Reanalysis project (CDAS-1, 1.875°x1.904726°). Daily temperature from the India Meteorological Department (HRDGT, 1°x1°) and NOAA NCEP/NCAR Reanalysis project (CDAS-1, 1.875°x1.904726°).

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