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Exploring the Limits of Flood Forecasting in Mountain Basins by using QPE and QPF Products during Summer Convection

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Abstract

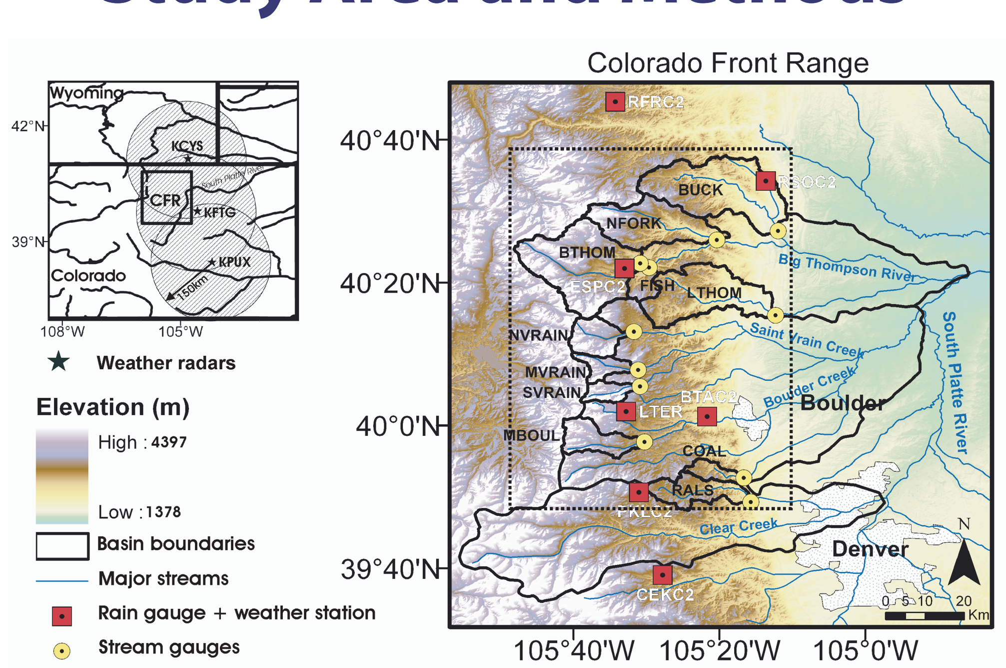
This research work explores the predictability characteristics of floods and flash floods by coupling high-resolution precipitation products to a distributed hydrologic model. The research hypotheses are tested in multiple watersheds of the Colorado Front Range (CFR) under warm-season precipitation. Rainfall error structures propagate into hydrologic simulations with added uncertainties introduced by model parameters and initial conditions. Specifically, the following science questions are responded: (1) What is the utility of Quantitative Precipitation Estimates (QPE) for high-resolution hydrologic forecasts in mountain watersheds of the CFR?, (2) How does the rainfall-reflectivity relation determine the magnitude of errors when radar observations are used for flood forecasts?, and (3) What are the spatiotemporal limits of flood forecasting in mountain basins when radar nowcasts are used in a distributed hydrological model? Results reveal that radar and multisensor QPEs lead to an improved hydrologic performance compared to simulations driven with rain gauge data only. In addition, hydrologic performances attained by satellite products open new avenues for forecasting in regions with limited access and sparse observations. Hydrologic simulations are shown to be sensitive to the uncertainties introduced by the reflectivity-rainfall (Z-R) relation. This suggests that site-specific Z-R relations, prior to forecasting procedures, are desirable in complex terrain regions. Radar nowcasting experiments show the limits of flood forecasting and their dependence functions on lead time and catchment area. Across the majority of the basins, flood forecasting skill decays with lead time, but the functional relation depends on the interactions between watershed properties and rainfall characteristics. Both precipitation and flood forecasting skills are noticeably reduced for lead times greater than 30 minutes. The scale-dependence of hydrologic forecasting errors demonstrates reduced predictability at intermediate-size basins. Overall, the fusion of high-resolution radar nowcasts and the convenient parallel capabilities of the distributed hydrologic model provide an efficient framework for generating real-time flood forecasts suitable for operational environments.

Objectives

Our objectives are oriented toward an evaluation of the current capabilities for flood forecasting in mountain regions. This poster reports on the following steps in this process:

- Hydrological intercomparison of precipitation inputs of different origin.
- Importance of site specific Z-R relations for flood forecasting based on reflectivity fields.
- Flood forecasting skill and reflectivity lead time dependence.
- Effects of spatial scale on the propagation of predictive uncertainties in flood forecasting.

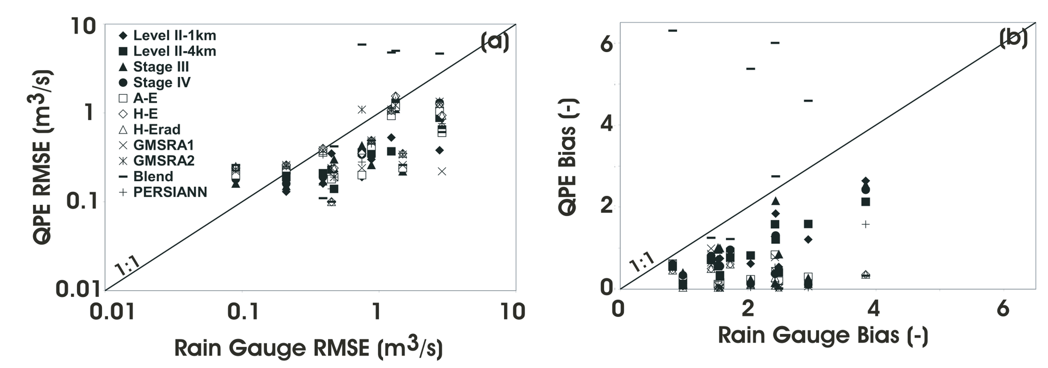
Study Area and Methods



- Eleven study basins with drainage areas ranging between 35 and 360 km^2.
- Region experienced historic floods due to convective storms during past summer seasons.
- High availability of weather stations, radar, satellite and streamflow observations in 2004, 2005 and 2006, when significant storm events occured.
- Ensemble Quantitative Precipitation Forecasts (QPF) produced using the Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN, Dixon et al.1993) model. TITAN is a extrapolation nowcasting technique.
- The Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator (tRIBS, Ivanov et al. 2004) model used to perform forecasting assessments.
- Complexities in rainfall, soils, vegetation and topography are accounted through tRIBS.
- Parallel computations, based on domain decomposition, performed at a supercomputer.

Hydrologic Utility of QPE

When used in distributed hydrologic models, distributed precipitation inputs were found to be skillful in accurately predicting timing and magnitude of flood events in mountain catchments (Moreno et al. 2012).

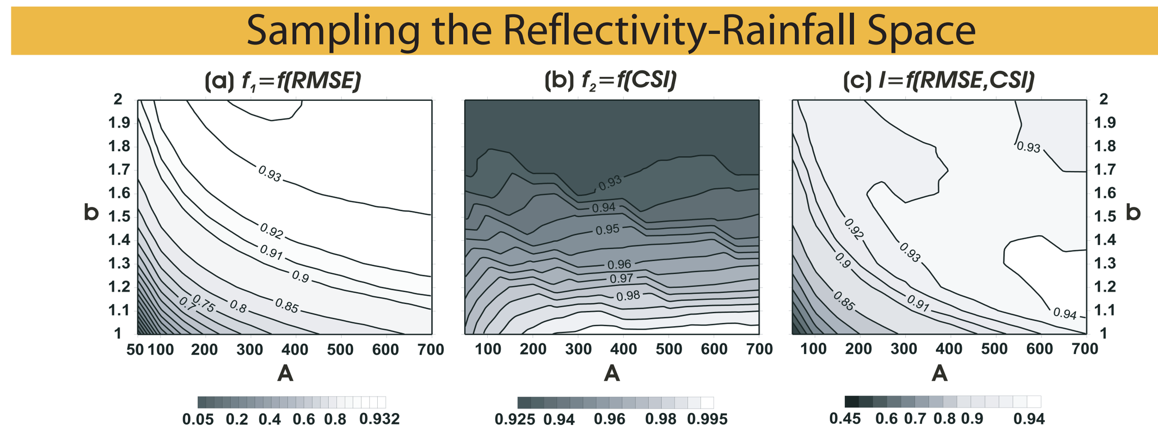


Comparison of QPE (4km, 1h) hydrologic skill relative to rain gauge simulations for three selected storms in summer 2004 at four study basins. (a) Outlet discharge RMSE, (b) Outlet discharge bias. Relative to rain gauge forcing, radar and multisensor QPEs, that preserve small storms relative to the basin area, have advantages in terms of runoff prediction. Some satellite QPEs (e.g. PERSIANN) also show better performances than rain gauges with respect to streamflow timing and volume for most cases.

Z-R Induced Uncertainties

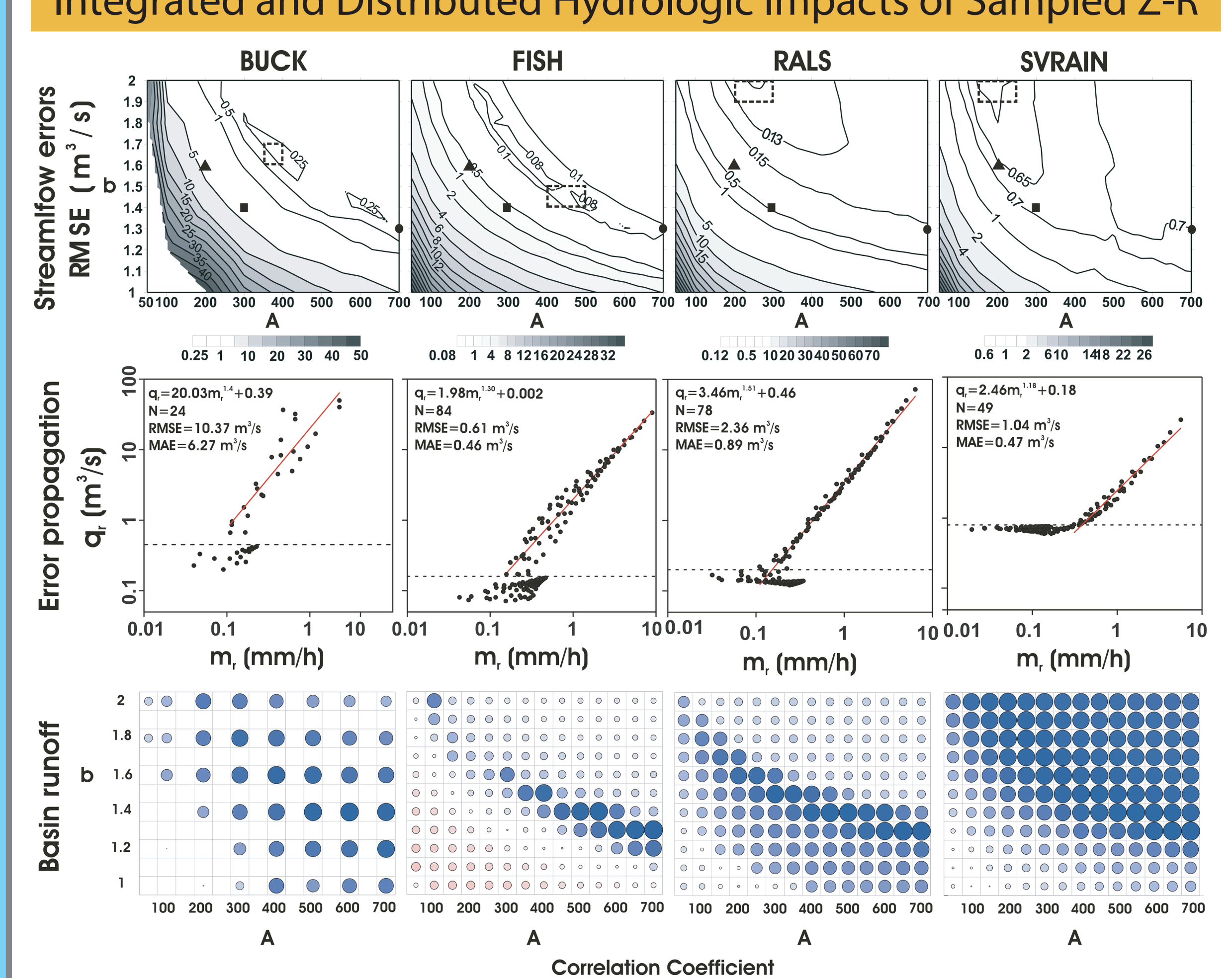
Errors in rainfall estimation from the radar reflectivity-rainfall relation ($Z=AR^b$) are expected to propagate into hydrologic simulations determining the quality of flood forecasts. Use of NWS default relations ($Z=300R^{1.4}$ ■, $Z=200R^{1.6}$ ▲) without preliminary calibration, introduce significant uncertainties when issuing QPFs (Moreno et al. in press).

Sampling the Reflectivity-Rainfall Space



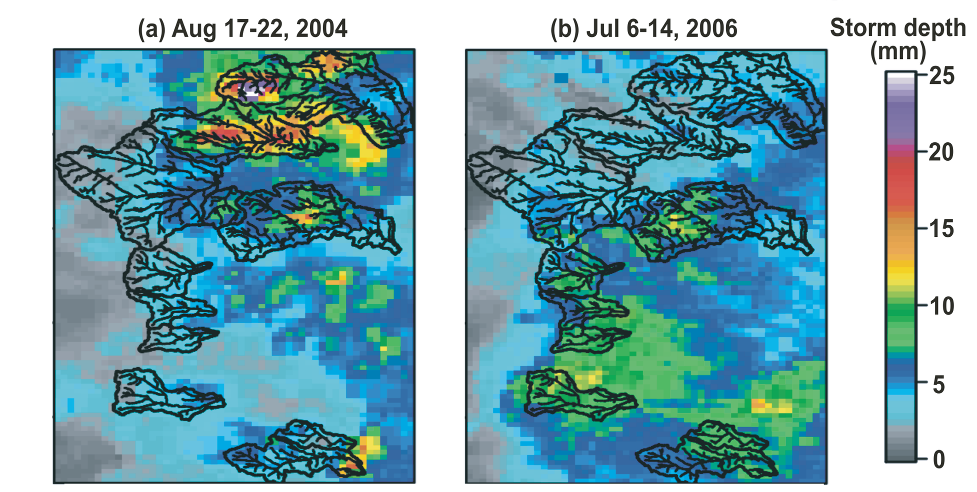
Different values of A and b were sampled to test the radar-derived rainfall field with respect to four rain gauges during summer 2004. Metrics include (a) Sum of RMSE, (b) Mean CSI, and combined function (c) I. I is expected to be maximized.

Integrated and Distributed Hydrologic Impacts of Sampled Z-R



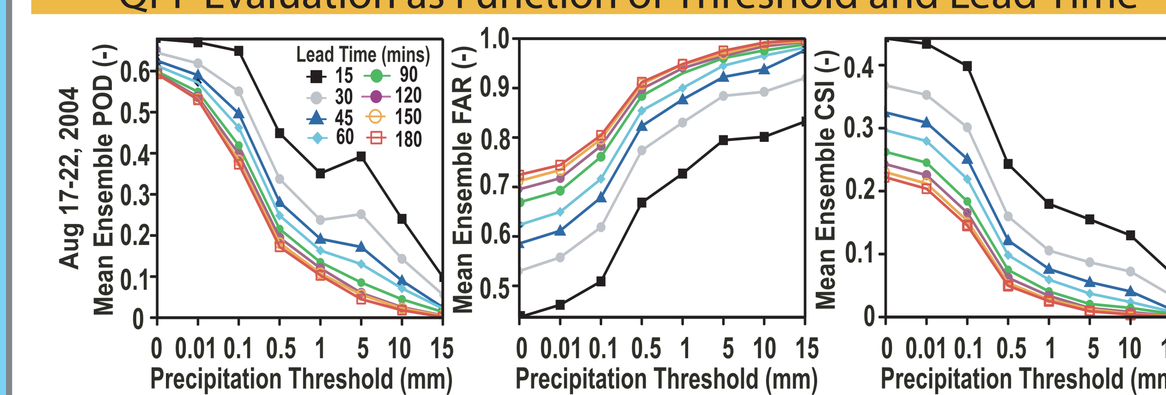
Hydrologic evaluation of different A-b combinations reveal significant differences in streamflow and distributed runoff among Z-R relations. Resulting errors in precipitation transmitted to hydrologic results following power-law expressions.

Limits to Flood Forecasting Skill

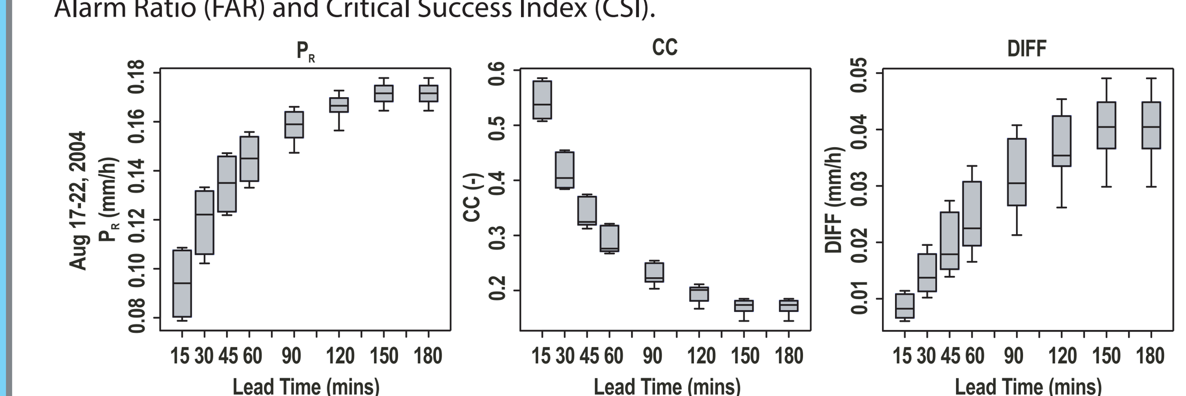


Two study periods were selected from Level II radar data (1km, 15min). Hydrologic responses were significant across the eleven basins and lasted a few days at the largest basins. Peak flows ranged between 1 and 15 m^3/s.

QPF Evaluation as Function of Threshold and Lead Time

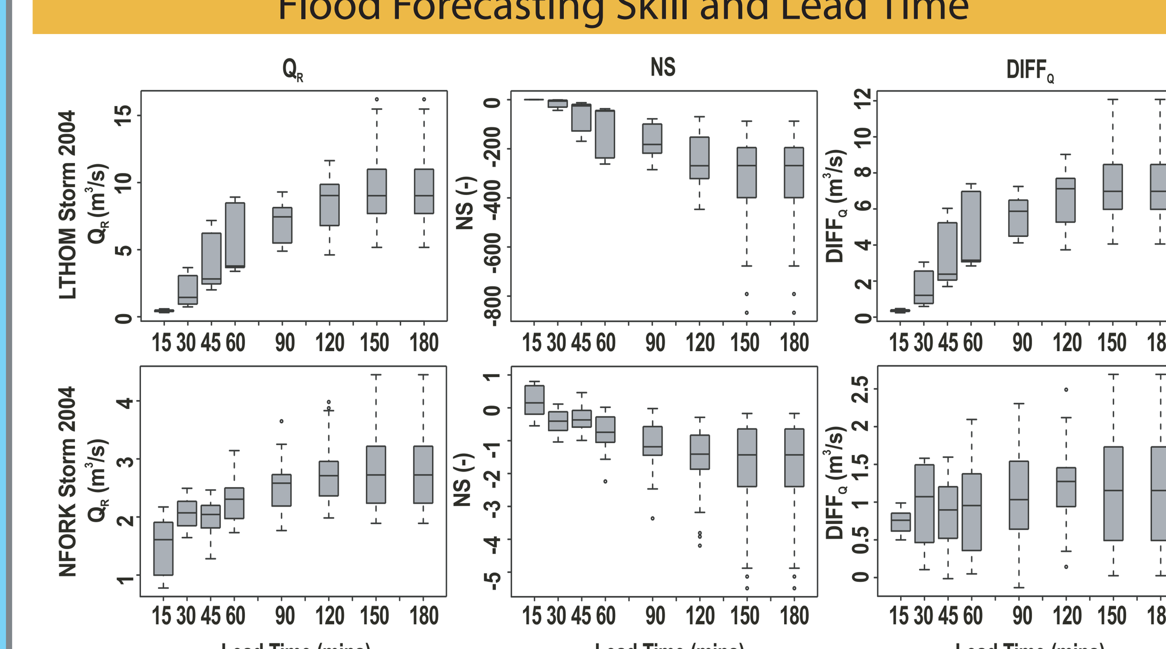


Analysis of ensemble QPF, in terms of QPE observations in CFR, reveals that probability of predicting occurence of precipitation decreases with lead time and rainfall magnitude. Categorical verification metrics include the mean ensemble Probability of Detection (POD), False Alarm Ratio (FAR) and Critical Success Index (CSI).



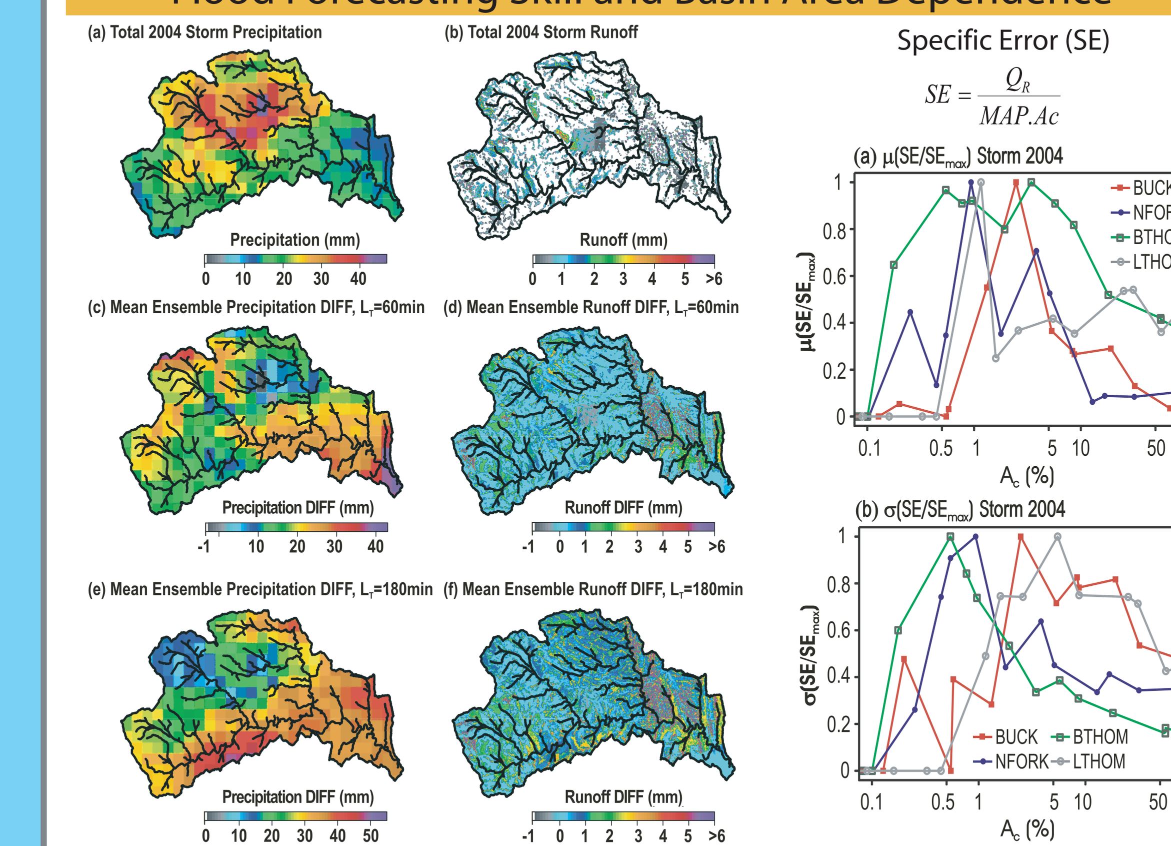
Across the CFR region, the most noticeable decrease in prediction skill occurs between 15 and 45 min lead times. Forecasts quality do not longer worsen beyond 150 min. Presence of positive and growing DIFF values across lead times indicate that the nowcasting model tends to overestimate precipitation values, increasing the number of false alarms, specially at large lead times. Metrics include the space-time averaged Root Mean Square Error (P_R), Correlation Coefficient (CC) and Mean Ensemble Difference (DIFF).

Flood Forecasting Skill and Lead Time



Hydrologic flood forecasting skill decreases with lead time but functional relations follow different patterns as a result of the interaction between properties of forecasted rainfall at individual watersheds and exceedence of hydrologic thresholds at large lead times. Uncertainty spread between ensemble members is larger at large lead times. Except by some small-size, snow-dominated basins, flood forecasting skill is not better than forecasted mean for lead times greater than 30 minutes.

Flood Forecasting Skill and Basin Area Dependence



- Despite changes in the spatial distribution of forecasted rainfall with lead time, only changes in the magnitude of runoff production are triggered as evidence of physical controls on the local flood potential.
- A characteristic pattern is revealed in the scale dependence of specific error (SE) at different lead times. Basin areas coinciding with typical size of convective storms experience the highest flood forecast errors with the largest differences among ensemble members.
- The spatial distribution of rainfall systems and watershed properties (e.g. soil permeability and topographic slope) dictate the shape of the scale-dependence as they control rainfall error propagation downstream and modulate ensemble dispersion across watersheds and lead times.

Conclusions

- The study results indicate that the use of distributed precipitation products in a distributed hydrologic model allows capturing the spatio-temporal variability of streamflow response. Relative to rain gauge forcing, radar, multisensor and some satellite QPEs that capture intensity and spatial variability of precipitation, especially intense localized storms, show advantages in terms of runoff prediction.
- Use of operational radar reflectivity-rainfall (Z-R) relations generate profound changes in the estimation of rainfall intensities that lead to streamflow error generation. Uncertainties propagate from rainfall to discharge estimations following power law expressions beyond a particular threshold. Thus, flood forecasting efforts benefit from establishing site-specific relations (e.g. $Z=700R^{1.3}$) for the season of interest using comparisons with local observations.
- Flood forecasting skill decreases with lead time, but the functional forms follow different patterns as a result of the interaction with watershed properties. Consistently with rainfall prediction characteristics, flood forecasting skill is not better than the forecasted mean for lead times greater than 30-min. Snowmelt-dominated basins have a more limited impact of rainfall uncertainties on the predicted discharges.
- We found that catchment areas that coincide with the typical size of convective storm systems experience the highest and more disperse values of SE, making predictability more dificult at these scales, principally due to an increase in runoff production that result in larger runoff coefficients. The typical size of convection systems and watershed properties control the shape of the specific error function.
- ***We found that flood predictability was most limited in basins of size between 2 and 20 km^2 due to the coincident storm scale in these mountain areas. Predictability at smaller and larger scales is dictated by the constituent basin properties and the averaging effect of precipitation.***

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Acknowledgments

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