J4.10 OPERATIONAL RAINFALL AND FLOW FORECASTING FOR THE PANAMA CANAL WATERSHED

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1. INTRODUCTION

In 1998 and as part of a science cooperation and technology transfer effort, the Hydrologic Research Center (HRC) and collaborators designed and implemented at the Panama Canal Authority (PCA) a prototype forecasting system for the real time rainfall forecasting over a number of small sub-catchments of the 3,200-sqkm mountainous Panama Canal Watershed in Panama (Figure 1). The system (called PANMAP) uses as input ETA forecasts (on an 80-km grid) and observations from surface hydrometeorological stations, upper air radiosondes, and a 10-cm weather radar, to produce mean areal precipitation estimates and forecasts within the Watershed on scales of 150-400 km^2 with a maximum 12-hour lead time and with hourly resolution. The system design combines embedded cloud models and state estimators for data assimilation and uncertainty estimation (*Georgakakos et al. 1999*). The rainfall forecasts and associated forecast variance are fed into operational hydrologic models, implemented for each Watershed sub-catchment within the framework of the U. S. National Weather Service River Forecast System (NWSRFS). The hydrologic model (SS-SAC, *Sperfslage and Georgakakos, 1996*) combines an adaptation of the Sacramento soil moisture accounting model with a robust state estimator design for real time updating from flow observations and forecast variance generation. The PCA is using the system operationally since October 1998 and the present paper presents results from an evaluation of system performance that is currently being performed using the operational data obtained by the system.

The next section describes the system design and outlines some of the salient features of the system. Section 3 describes the methodology for the evaluation of the operational forecasts and the statistics used for the validation, while section 4 presents selected results. Section 5 contains concluding remarks.

2. INTEGRATED SYSTEM DESIGN

PANMAP is a prototype operational mean areal rainfall estimation and forecast system with a full uncertainty package. The main system components and links are shown schematically in Figure 2. The mean

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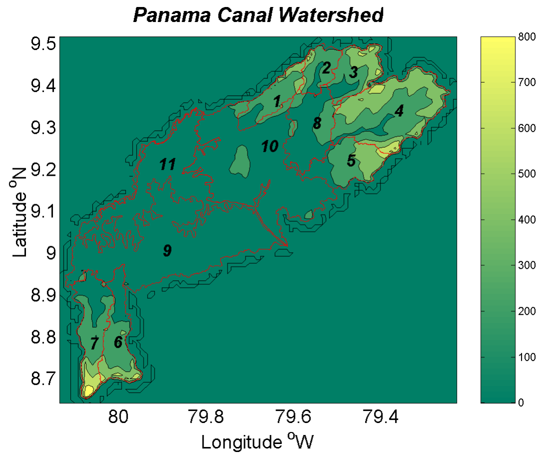

Figure 1. Panama Canal Watershed topography (color scale in m) and sub-catchments used in PANMAP. "Sub-catchment" 11 is Lake Gatun.

areal rainfall estimation component, designed and implemented in collaboration with University of Iowa researchers (see *Georgakakos et al. 1999*), quality controls the radar reflectivity data, accounting for ground clutter and anomalous propagation, develops real time estimates of a bias adjustment factor used to merge raingauge and radar rainfall estimates, and merges hourly estimates of rainfall from radar low-elevation scans, mapped onto the HRAP grid, and automated ALERT-type raingauges. An adaptive Kalman Filter is used to estimate the values of the adjustment factor using intervals of 50 "wet" hours in real time. Uncertainty for the merged estimates of mean areal precipitation for each sub-catchment are produced in real time and are used by the other components of PANMAP. Prior to the merging of radar and raingauge data, spatial interpolation of the raingauge data is done using Kriging.

The precipitation forecast component is based on potential theory air-flow models (e.g., *Tateya et al. 1991*) for determining the areas of significant updrafts generated by the three-dimensional interaction of the mountainous topography with the approaching 700 mbar wind, and stochastic-dynamical cloud microphysical models (e.g., *Lee and Georgakakos 1996)*. The model developed is forced by operational ETA forecasts of upper-air boundary conditions on scales of 80 km on the side and it is used effectively to distribute rainfall in space and time on the basis of ETA operational forecasts. It is coupled to a state estimator to allow real-time updates of cloud- and rain-water from

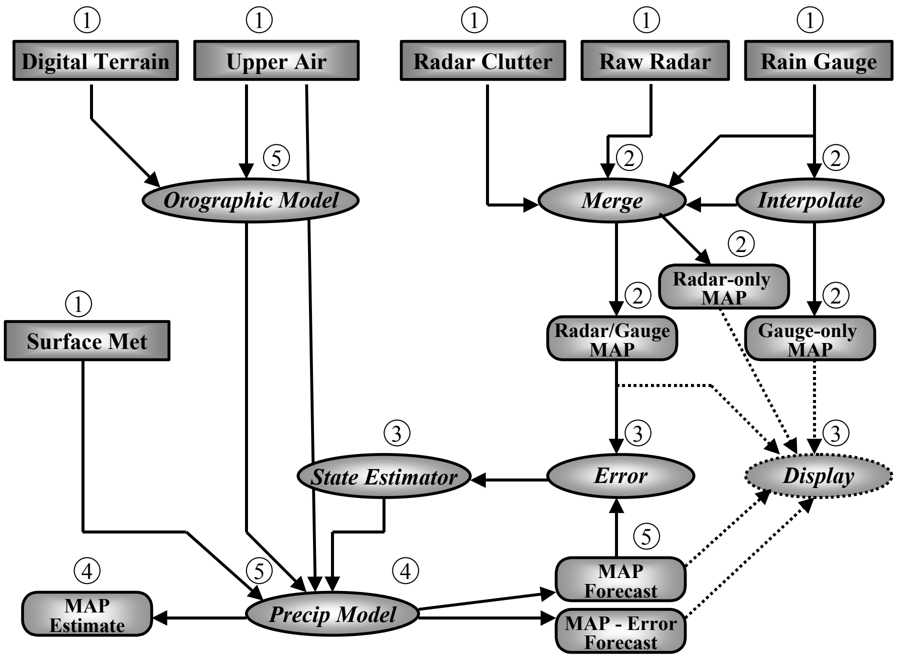

Figure 2. PANMAP system components and links.

hourly mean areal precipitation observations and to produce estimates of rainfall forecast variance in real time. Surface meteorological data are used to determine rapidly changing surface moisture conditions between ETA forecasts and radiosonde launches to facilitate the production of important short-term rainfall forecasts of 1- to 6-hour duration. The components included in the parsimonious model formulation are:

- (a) orographic updraft enhancement,
- (b) convective updraft development,
- (c) advection of storm cloud and rain water,
- (d) model state estimation (error variance propagation and updating).

Significant effort was placed on the development of an input interface to ingest data. As it is implemented, the PANMAP integrates 15-minute information from the 10-cm weather radar located on the Engineers Hill in Panama City, hourly information from the more than 30 automated hydrometeorological ALERT systems located throughout the Panama Canal Watershed, radiosondes for upper air information launched daily or twice daily in Panama, and the operational mesoscale meteorological ETA model predictions produced at the U.S. National Oceanic and Atmospheric Administration. The system also integrates information from digital terrain elevation data for surface wind and rainfall analysis. The products of PANMAP are: detailed information on the current state of the atmosphere over each of the Panama sub-catchments, current radar and raingauge rainfall maps, and forecast advisories for hourly rainfall amounts with a maximum forecast lead time of 12 hours. These products are used by meteorologists and hydrologists of PCA's Meteorology and Hydrology Section in their operational diagnosis and prediction of severe events and day-to-day weather. A user's guide for PANMAP is in *Sperfslage et al. (1999)*.

PANMAP rainfall forecasts and associated variance are fed into the streamflow prediction model, which generates flow forecasts and variances in real time. The streamflow model used is an adaptation of the U.S. National Weather Service Sacramento soil moisture accounting model complemented with a conceptual kinematic routing model and running as part of the NWSRFS. The state-space form of the model is used (called SS-SAC), as developed by *Georgakakos et al. (1988)*, tested by *Georgakakos and Smith (1990)* in an official WMO model intercomparison project, and implemented for national real-time operational use as part of the National Weather Service River Forecast System by *Sperfslage and Georgakakos (1996).* The development of the final form of the model and tests with historical data from the Panama Canal Watershed is documented in *Georgakakos et al. (1999).*

The integrated hydrometeorological system was tested with limited available historical data prior to operational use and during model development (during the period 1997-1998), and initial model parameter adjustments were made at that time. Since 1998, the system is running in an operational environment without any adjustments in models or parameters. The next section presents early results of the first evaluation of operational system performance performed since the time of system implementation.

3. PERFORMANCE EVALUATION

Analysis of the PANMAP forecasts for the two July-December 2000 and August-December 2001 (in wetter half of the year) was performed with performance measures that are commensurate to the intended use of the rainfall forecasts for hydrologic purposes. The error in forecasting the volume of rainfall is the primary such measure used as a bulk statistic for validation, but individual forecasts with lead times from 1 hr to 12 hrs were also considered during periods with significant storm rainfall. The analysis examined the use of a variety of input data such as the use of ETA forecasts of surface and upper-air fields (temperature, pressure, humidity, winds), and the use of upper air radiosonde observations and surface ALERT data for the short-term forecast of surface mean areal rainfall over 10 sub-catchments of the 3,200-km^2 Panama Canal Watershed. The validation effort was performed in close collaboration with the staff of the Meteorology and Hydrology Section of the PCA.

Figure 3 exemplifies dependence of the residual means on the observations means for three-hourly volume forecasts for periods with at least one hourly rainfall observation greater than 6.35mm/h. Yellow symbols correspond to July-September. Blue symbols correspond to October-December. The 50% bounds are also shown for the average residual means. The thick black line at the 0% residual mean value is the line of no bias. It is evident that the operational PANMAP software tends to overestimate the light amounts of three-hourly rainfall in all months of record and for all sub-catchments of the Panama Canal Watershed. It is also evident that the software reproduces the higher observed rainfall amounts without significant or consistent bias and independent of season within the wetter half of the year (no significant differences in trend exist between the yellow and the blue symbols). For example, to get a +/- 50% bias in three-hourly amounts, the observed average rainfall should be at least 3mm/hr.

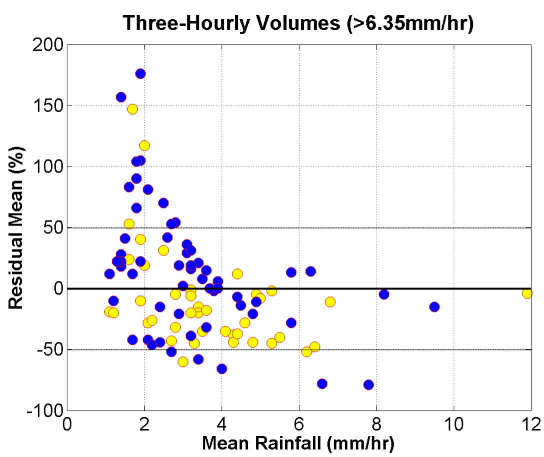

Figure 3. Forecast residual mean as a percent of the observed mean versus the observed mean for three-hourly volumes of mean areal rainfall over sub-catchments in the Panama Canal Watershed. Yellow is for July-September and blue is for October-December in years 2000 and 2001.

Figure 4 exemplifies results obtained for individual sub-catchments of the Panama Canal Watershed for three-hourly forecast volumes (analogous to the results shown in Figure 3). The results shown are for the mountainous eastern sub-catchments. These sub-catchments receive much higher hourly mean areal rainfall than the rest of the sub-catchments (maximum observed mean areal rainfall of about 11.5 mm/hr for the eastern sub-catchments compared to a maximum of about 4.5 mm/hr for the western sub-catchments). For three hourly forecasts, about 70% of the forecast cases are within +/- 50% of the observed values with more than 95% of the cases being within the +/- 100% bounds. There are more cases with negative bias than cases with positive bias found for the period of record with significant rainfall. There are no significant sub-catchment bias trends across the Canal Watershed.

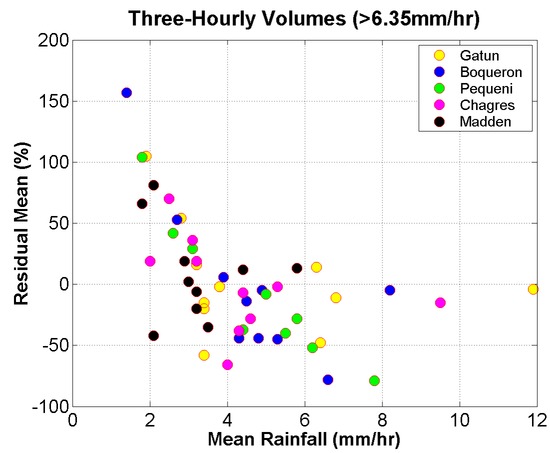

Figure 4. As in Figure 3 but with results shown for individual eastern sub-catchments for the wetter half of the years 2000 and 2001.

PANMAP uses a variety of input sources to produce rainfall forecasts. To understand the utility of each data type (e.g., ETA forecasts of wind, temperature, humidity; and upper-air radiosonde and automated surface meteorological observations) for rainfall volume forecasts, a number of sensitivity studies were conducted. The PANMAP system was re-run for the test period using a variety of input data configurations. Due to space limitations, detailed results are not shown but the next section contains our significant conclusions from these studies. In this section, we present an example of rainfall and flow hourly forecast performance of the integrated system for an individual significant storm event that occurred in late December 2000 over the Watershed and which caused flash floods in several sub-catchments.

Figure 5 shows the hourly mean areal rainfall forecasts (in blue) and associated observations (in red) produced by PANMAP for each of four eastern mountainous sub-catchments of the Panama Canal Watershed for the period 28-31 December 2000. The results indicate that the short-term hourly-rainfall forecasts possess skill for these sub-catchments with some time shifts present and with overestimation of lower rainfall rates in some instances.

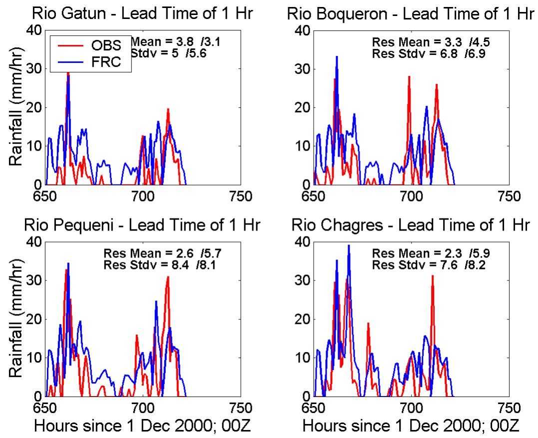

Figure 5. Hourly mean areal rainfall forecasts (blue) and observations (red) for the significant storm event of 28-31 December 2000 and for the eastern mountainous sub-catchments of the Panama Canal Watershed. The ratios of residual to observation means and residual to observation standard deviations are shown in each case for the storm period.

The result of using PANMAP mean areal rainfall *forecasts* as input to the SS-SAC hydrologic forecast model for individual sub-catchments is exemplified in Figure 6 for the 154-km^2 Rio Pequeni sub-catchment in the eastern mountainous portion of the Panama Canal Watershed (sub-catchment no. 3 in Figure 1). For inter-comparison, the hydrologic model hourly flow forecast is also shown in Figure 6 (lower panel) when *observed* mean areal rainfall is used as input. The results in both panels indicate underestimation of the early phases of the flash flood flow with more accurate predictions during the second wave of the event and with overestimation near the end of the storm period. This is likely due to erroneous hydrologic model initial conditions and/or the result of model parameter error. PANMAP *forecast* forcing resulted in moderate underestimation of the flood flows early in the event compared to *observed* rainfall forcing, with essentially accurate reproduction of the second significant wave of flood flows.

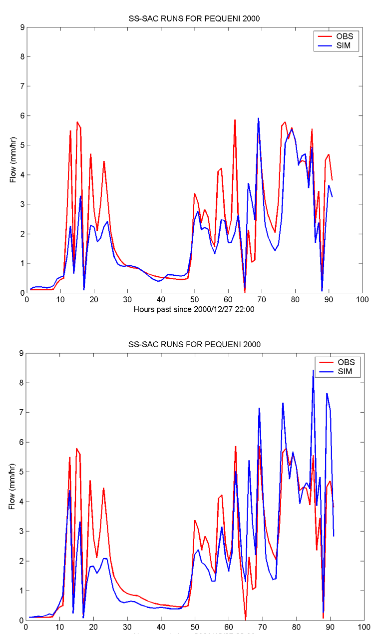

Figure 6. Hourly forecasts (blue) and observations (red) in mm/h of Rio Pequeni flow for the period 28 – 31 December 2000. Upper panel is for PANMAP *forecast* input and lower panel is for *observed* mean areal rainfall input.

4. CONCLUDING REMARKS

The primary conclusion from the performance evaluation effort is that the coupled system produced useful forecasts during times of heavy rainfall that contributed to producing effective management decisions during these periods. The results of the on-going evaluation effort obtained so far indicate that the PANMAP forecasts have lowest bias when radiosonde (RAOB) data are used to produce input to the rainfall prediction component for forecast lead-times out to 3 hours, and when new ETA forecasts are used to produce input to the rainfall prediction component for forecast lead-times from 6 to 12 hours. The use of surface ALERT data exclusively during storm periods yields reasonable hourly nowcasts, but results in significant underestimation of rainfall volume for longer lead-times. There is an overall overestimation (in some cases significant) of low rainfall amounts that is persistent throughout the validation period, with the best results obtained for the heavier rainfall amounts. Best forecast performance is found for the northeastern mountainous catchments of Rio Gatun, Rio Boqueron, Rio Pequeni and Rio Chagres and for the Lake Gatun area in the central region of the Panama Canal Watershed. The use of the PANMAP forecasts and uncertainty as inputs to the SS-SAC hydrologic model produced skillful short-term flow forecasts for sub-catchments of area down to 150 km^2.

Current efforts are devoted to the determination of the reliability of the forecast variance estimates for rainfall and flow forecasts of multiple lead times.

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