Journal of Hydroinformatics | 04.1 | 2002

US corporate technology transfer in hydrometeorology

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ABSTRACT

Corporate technology transfer by US non-governmental organizations with the substantial involvement of university faculty is a new activity in hydrometeorology. The issues involved in such US corporate technology transfers are discussed by way of two examples selected from the activities of the Hydrologic Research Center, a non-profit-making public-benefit research and technology transfer corporation in San Diego, California, USA. The projects discussed are: (a) the development and implementation of a robust state estimator for national use within the US National Weather Service River Forecast System, and (b) the development and implementation of a prototype multi-sensor rainfall forecasting system for the Panama Canal Authority. The issues covered include technical ones associated with improving theoretical formulations for robust operational performance, those associated with the necessary reciprocal education between modellers and field personnel, and the accommodation of the educational objectives of participating postdoctoral associates.

Key words | education, floods, hydrometeorology, rainfall, technology transfer

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INTRODUCTION

Hydrometeorology is a rapidly advancing area of the geosciences with applications, such as real-time flood and flash-flood prediction, or operational water resources management, that are directly pertinent to the daily life of society (Loucks 1989; Waggoner 1990; NRC 1991). The subject matter of hydrometeorology consists of natural phenomena that show a wide spectrum of temporal and spatial variability (from local rain-rates to continental-scale soil-moisture fields). Predictability horizons for such phenomena vary from a few minutes to a few months, and there is significant uncertainty associated with any relevant operational predictions. Based on high-quality data, basic research in hydrometeorology addresses questions of cause and effect. The evolving end-results are an improved understanding of the phenomena and improved predictive models. However, there are urgent societal needs for the management of the extremes of several hydrometeorological variables. This implies that operational hydrometeorological systems must be formulated and designed based on evolving models whose predictions carry significant (and, in some cases, non-quantifiable) uncertainty. As such, the transfer and modification of technology from basic research to applications, and the communication of essential research from applications to basic research are reciprocal links that must be facilitated. Necessarily then, basic research through strong collaboration with university researchers, internal applied research and close links to field operations are synergistic constituent characteristics of sustainable technology transfer organizations (Ettema & Kennedy 1990; Georgakakos 1995).

This paper draws from the experience of the Hydrologic Research Center (HRC) to discuss two technology transfer applications and associated issues, and addresses the areas of system and model formulation, implementation and testing, and the training of field personnel. A brief overview of the work is presented in each case. The interested reader is encouraged to consult the references given at the end of this paper for detailed discussions of technical issues.

OPERATIONAL STATE ESTIMATION

Brief research history

Research results on the use of state estimators with conceptual hydrological models for real-time flow forecasting have reported improvements in short-term model forecasts (Kitanidis & Bras 1980*a, b*; Georgakakos 1986*a, b*). The estimators provide a useful framework for (a) the utilization of real-time flow data for updating model state variables, and (b) the generation of estimates of forecast error in real time. The first aspect is important because in most practical applications flow observations carry a smaller uncertainty than the rainfall and potential evapotranspiration input used by the model. Consequently, state estimators contain useful information that should be included in the model. The second aspect provides an appropriate description of the model's forecasting ability for applications (e.g. Krzysztofowicz 1983).

In spite of the benefits that state estimators bring to real-time forecasting, their operational implementation for flow forecasting has been rather limited in the US (see Bae *et al*. (1995) for one of the few recent field implementations). The probable reasons for this stem from the complexity of the theory and the implementation of state estimators (which impose a substantial training burden on field users of the software), and also from the variety of existing possible designs (some not very robust) of state estimators with free parameters.

Although some training in the theory of state estimation is always necessary, the design of robust estimators, with little or no interaction with the user, is now possible. Georgakakos *et al*. (1988) developed the theory and evaluated the applications of the hydrological forecast system (HFS), also called the state space Sacramento model (or more recently SS-SAC), based on well-tested conceptual hydrological models and a state estimator with a few free parameters. The hydrological component of SS-SAC uses a modified version of the Sacramento soil water accounting model (see Peck (1976) for the original formulation, and Georgakakos (1986*a*) for the modified version) coupled to a non-linear reservoir model for channel flow routing (Georgakakos & Bras 1982). The state estimator was based on a new robust design that explicitly associates state estimator parameters with (a) hydrological model physics, and (b) *a priori* degree-of-belief estimates of input and parameter uncertainty. The new estimator design was tested in a simulated intercomparison project organized and executed by the World Meteorological Organisation (WMO) from 30 July to 8 August 1987 at the University of British Columbia (UBC), Vancouver, BC, Canada (World Meteorological Organisation 1992). The tests used simulated real-time conditions and actual data from two different hydrological basins. They showed the superior performance of SS-SAC compared with the performance of the hydrological components running without a state estimator (see Georgakakos *et al*. (1988), Georgakakos & Smith (1990) and Georgakakos (1994) for various test results pertaining to SS-SAC forecast accuracy and reliability). Georgakakos & Sperfslage (1995) document the software implementation of this stand-alone version of SS-SAC.

Sperfslage & Georgakakos (1996) document the operational implementation and testing of SS-SAC as part of the US National Weather Service River Forecast System (NWSRFS) on a workstation environment. SS-SAC is now Operation 22 within NWSRFS and is referred to as the state space Sacramento operation to distinguish it from the pre-existing NWSRFS SAC operation (deterministic Sacramento model). In collaboration with the Office of Hydrology of the US National Weather Service, three test basins of approximate area 1,000 km^2 were identified in Oklahoma. The SS-SAC and SAC operations were used in parallel to produce flow forecasts for these basins from October 1994 until March 1996, using the operational databases of the Arkansas–Red River Forecast Center (ABRFC). The primary conclusion of these operational tests was that SS-SAC exhibited a significantly better performance than SAC in most cases of short lead times (duration 6 h) because it reduced the largest flow prediction errors (Figure 1). For longer lead times, the quality of the forecasts of mean areal precipitation dominated the performance of both systems, with the SS-SAC operation exhibiting significantly better performance for two of the basins in this case also. The two systems gave comparable results for the third basin and for lead times greater than 12 h.

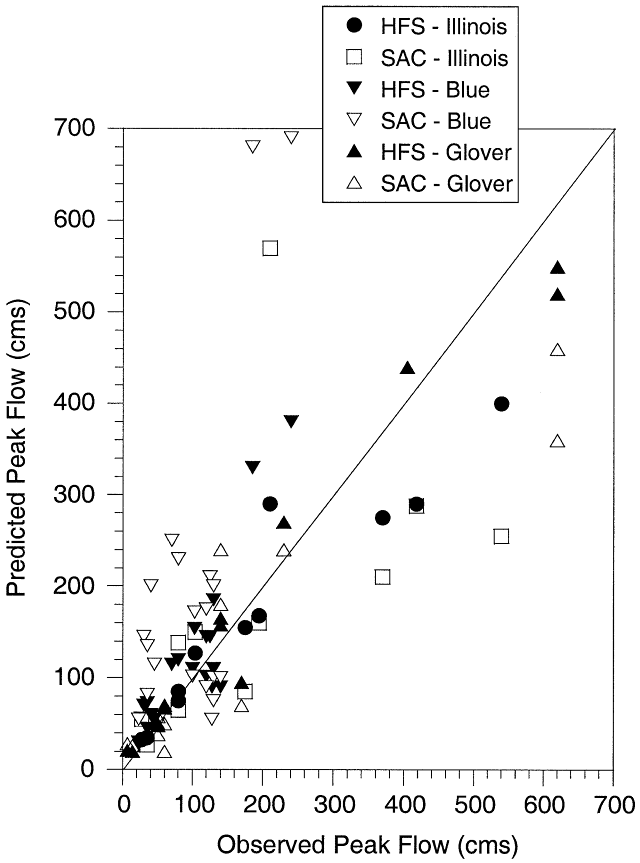

Figure 1 | Intercomparison of peak flow errors for HFS/SS-SAC (filled symbols) and SAC (open symbols) for the three test basins in Oklahoma. Both systems run using operational data (October 1994–March 1996).

Formulation basics

Express the conservation of water volume principle in all model compartments as

$$\frac{\mathrm{d}\boldsymbol{x}(t)}{\mathrm{d}t} = \boldsymbol{f}(\boldsymbol{x}(t)) \quad (1)$$

where $\boldsymbol{x}(t)$ is the state vector whose elements are the water volumes in the individual water compartments of all the conceptual models of SS-SAC (i.e. all the compartments of the soil-water model and all the compartments of the channel routing model), and $\boldsymbol{f}(\boldsymbol{x}(t))$ is a vector function with elements that represent the inflows and outflows of individual water compartments (vectors are shown in boldface type). Equation (1) is a prognostic equation, and may be used to obtain predictions of future values of each element of $\boldsymbol{x}$ from present values and from forecasts of model inflows such as precipitation and potential evapotranspiration.

Flow forecasts are expected to contain errors because of (a) errors in the formulation of the model components, (b) parameter inaccuracies arising from the calibration of the model with limited data, and (c) inaccurate forecasts of precipitation and potential evapotranspiration (which constitute SS-SAC input). While within SS-SAC there is no way to control the magnitude of input errors, it is possible to minimize forecast errors due to inaccurate past input and the inaccurate specification of parameter values. In addition, it is possible to produce an estimate of the variance (or standard deviation) of SS-SAC flow forecast errors. The minimization of forecast errors may be accomplished with model-state updating from real-time observations of discharge. The algorithm that does this is called a state estimator (e.g. Kalman filtering, as in Gelb (1974) and Bras & Rodriguez-Iturbe (1985)), and an estimate of forecast errors may be obtained as part of the state estimator formulation.

The updating of the forecast state vector $\boldsymbol{x}$ at time t_k, when a flow observation $Q_O(t_k)$ becomes available, is based on the expression

$$\boldsymbol{x}_u(t_k) = \boldsymbol{x}_f(t_k) + \mathbf{g}(t_k)\ (Q_O(t_k) - Q_f(t_k)) \quad (2)$$

where subscripts 'u' and 'f" signify updated and forecast quantities, respectively, at time t_k. The vector of weights $\mathbf{g}(t_k)$ depends on (a) the particular formulation of the SS-SAC model components, (b) the expected errors in the SS-SAC forecasts and (c) the expected errors in the flow measurements. Updating follows a forecast of the model state $\boldsymbol{x}_f(t_k)$ and of flow $Q_f(t_k)$ at time t_k. This produces an updated estimate of state $\boldsymbol{x}_u(t_k)$ at time t_k to be used as the initial condition for the next cycle of the forecast sequence that uses the prognostic Equation (1).

To determine the expected errors in forecasts and observations, a set of variance prognostic and updating equations is formulated to complement the set of Equations (1) and (2). The variance equations are based on the prognostic state Equation (1) and on *a priori* degree-of-belief estimates of expected errors in input and model parameters. The linearization of non-linear functions in the model formulation is required, and the SS-SAC formulation is based on analytical expressions of all required derivatives. The form of the state estimator implemented in HFS is substantially different from typical implementations of linear or linearized state estimators (e.g. the Kalman filter and the extended Kalman filter). The interested reader is urged to consult the specific references cited for an in-depth explanation. A brief description of the prognostic variance equation is given in the following discussion. This equation is one element of the SS-SAC state estimator implementation that makes it robust and different from other state estimator designs.

The state covariance matrix $P(t)$ characterizes the expected errors in estimating the true state vector $\boldsymbol{x}(t)$. Georgakakos *et al.* (1988) and Rajaram & Georgakakos (1989) derive the prognostic equation for $P(t)$. The result is

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = F(t)P(t) + P(t)F(t)^T + \alpha_u M(t)U(t)M(t)^T + \alpha_p N(t)WN(t)^T \quad (3)$$

where $U(t)$ and W are covariance matrices corresponding to errors associated with the input to SS-SAC (precipitation and potential evapotranspiration estimates or forecasts), and with the estimates of the parameters of the SS-SAC models (modified Sacramento and stream-flow routing models), respectively. The matrices $F(t)$, $M(t)$ and $N(t)$ contain the derivatives of the elements of the function $\boldsymbol{f}(\ )$ (see Equation (1)) with respect to (a) the elements of $\boldsymbol{x}(t)$, (b) the input precipitation and evapotranspiration and (c) each of the parameters of the SS-SAC models, respectively. The parameters α_u and α_u are obtained from SS-SAC runs with historical data, so that the forecast error statistics predicted by the state estimator match the actual ones (e.g. time-uncorrelated residuals).

Equation (3) associates the state variance prognostic equation with the model physics (as described by the sensitivity matrices $F(t)$, $M(t)$ and $N(t)$), and with degree-of-belief estimates of the errors in the input forecasts (elements of matrix $U(t)$) and in the estimates of model parameters (elements of matrix W). For each drainage basin of application, these degree-of-belief estimates must be specified as SS-SAC system parameters by hydrologists with experience in the hydrology of the particular basin and in the use of the Sacramento model to simulate soil-water processes (see NOAA-Video 1999).

A recent operational field application

In collaboration with the staff of the California–Nevada River Forecast Center (CNRFC), the SS-SAC has been used since March 1998 for the operational short-term (6 h) prediction of the American River inflow to the Folsom Reservoir in California. The reservoir, through judicious management by the Bureau of Reclamation, protects the city of Sacramento from flooding, generates hydroelectric energy and enhances the quality of the downstream river waters.

The SS-SAC is applied to each of the North, Middle and South Fork headwater catchments of the American River, and the total inflow is computed as the sum of the three fork outflows suitably routed to the inflow point of the Folsom Reservoir. The variance of the total inflow is computed in real time assuming the mutual independence of forecast errors for the three forks. Estimates of the precipitation input error variance (e.g. $U(t)$ elements) were obtained from a statistical analysis of historical mean areal precipitation estimates and forecasts, while degree-of-belief estimates of parameter errors (e.g. W elements) were determined by HRC staff, who also developed the parameter values for SAC for each fork of the American River. Short historical records were used to estimate the values of α_u and α_p.

Table 1 shows the 6-h forecast performance statistics for the American River inflows to Folsom Lake, and those for the first period of SS-SAC operational use. The results show good real-time performance and are consistent with previous experience pertaining to SS-SAC predictions.

Issues

Perhaps the most important issue relating to the operational application of SS-SAC is the production of estimates for the values of the free-state estimator parameters. As mentioned above, degree-of-belief estimates for input and parameter error variances must be provided by

Table 1 | Statistics of Folsom Lake inflow (in cm). SS-SAC: 23 March 1998–7 October 1998

	Observed	Forecast	Residual
Time Steps	683	792	683
Minimum	13.02	43.58	
Maximum	914.40	908.53	
Mean	186.83	181.39	2.78
Median	192.80	187.60	0.17
Standard deviation	113.80	108.97	28.51
Var. expl. (%)			93.7

hydrologists who have experience of the particular basins concerned and of the Sacramento model. In the River Forecast Center there is usually the relevant expertise, and training the staff to calibrate and use SS-SAC is straightforward. There is less expertise in probabilities and statistics, and consequently training in the interpretation of the SS-SAC measures of the forecast uncertainty requires more effort, as does the determination of remedial measures in cases of poor state-estimator calibration owing to initial limited data records. It is also important to note that the use of covariance uncertainty measures within SS-SAC required several modifications in the original software configuration of the NWSRFS databases to accommodate the input–output and data storage associated with these measures.

From the HRC's perspective, the primary technology transfer process stops when the initial parameters of the SS-SAC have been determined and the training of RFC staff has been completed. In later phases, HRC staff may be involved in secondary technology transfer activities such as assisting with the validation of the operational forecasts in terms of both the mean forecast accuracy and the forecast variance reliability. In the case of the Folsom Reservoir application, HRC staff developed various ancillary products such as the second moments of reservoir inflow forecast volumes from 6-hourly discharge forecasts produced by SS-SAC. During the development of SS-SAC applications, frequent reports provided by the staff of the CNRFC as to the operational performance of the SS-SAC were instrumental in improving the parameter estimates of the state estimator.

The training potential for HRC post-doctoral and master's level staff in this application rests on gaining familiarity with the operational forecast system of the US National Weather Service, and in validating the existing SS-SAC formulation with the objective of identifying necessary improvements and further applied research topics. A study of the influence of mean areal precipitation forecast errors on the reliability of the SS-SAC flow-forecast variance, and a modification of the formulation of the variance equations to account for large transient mean areal precipitation errors are identified as significant future research objectives.

OPERATIONAL RAINFALL PREDICTION

Brief research history

In the early 1980s, a new class of conceptual models for real-time precipitation prediction was formulated, and was tested successfully on a hydrological scale (Georgakakos & Bras 1984*a, b*). These models conserved the liquid water equivalent in storm clouds, and used simplified micro-physical parametric relationships to express macro-physical water mass and mass flux as functions of hydrometeor drop-size distributions. State estimators were designed for these models to allow cloud and rain liquid water equivalents to be updated from real-time precipitation observations over the hydrological catchment area of interest. Tests of these models showed an improved performance for short lead times (up to 6 h) with respect to statistical models of local precipitation predictions. The primary advantages these models offered over detailed meso-scale numerical weather prediction models were that they were computationally efficient while retaining the essential storm cloud physics, they resolved finer spatial scales, and they incorporated frequent real-time information on precipitation rates in a consistent stochastic process framework.

Following these research developments in hydrometeorology, and for the purposes of (a) integrating information on hydrological and meteorological fluxes in real time, and (b) generating short-term flash-flood warnings (with hourly forecasts), coupled hydrological–meteorological systems were formulated and tested (Georgakakos & Hudlow 1984; Georgakakos 1986*a, b*, 1987; Bae *et al*. 1995). These systems integrate local precipitation prediction models with hydrological models on the catchment scale, both through the conservation of mass equations for water, and also through a feedback loop that updates the precipitation and hydrological model states from real-time observations of catchment mean areal precipitation and of stream-flow. These hydrometeorological forecast systems produce forecasts of mean areal precipitation and flow for the catchment areas of interest, together with estimates of forecast uncertainty. A simulated real-time comparison of these integrated hydrometeorological models with conventional models showed an improved performance in short- (6-h) and medium-range (up to 18 h) predictions of flood-peak timing and magnitude (Georgakakos 1986*b*). Georgakakos & Foufoula-Georgiou (1991) found that the benefit of using integrated hydrometeorological models for the real-time forecasting of flows is greatest when the forecast lead time is comparable with the time of response of the flash-flood-prone catchment areas of interest.

In recent years, following the same line of research, spatially distributed precipitation prediction models have been formulated with the ability to utilize weather radar data for generating gridded precipitation forecasts over regions greater than 10^4 km^2 with a 10-km resolution (e.g. Lee & Georgakakos 1990, 1996; French & Krajewski 1994; Dolcine *et al*. 1998). Typically, these models are appropriate for non-mountainous terrain, and they are designed for use in conjunction with current operational meso-scale numerical weather prediction models (i.e. the ETA model—a numerical weather prediction model—in the US, Mesinger 1996). Current active research towards improving rainfall predictions on the hydrological scale includes the improved utilization of weather radar data (French *et al*. 1995; Dolcine *et al*. 1998), the improved formulation of model uncertainty components (Grecu 1999; Georgakakos 2000), and the extension of model formulation for application to mountainous areas (e.g. Pandey *et al*. 2000).

Formulation basics

The differential equation expressing the conservation of cloud and rain liquid water equivalent mass is integrated along the vertical coordinate to yield the basic precipitation model equation (e.g. Lee & Georgakakos 1996)

$$\frac{\partial X(x,y,t)}{\partial t} = -u\,\frac{\partial X(x,y,t)}{\partial x} - v\,\frac{\partial X(x,y,t)}{\partial y} - h(x,y,t)X(x,y,t) + S(x,y,t) \qquad (4)$$

where the model state $X(x,y,t)$ is the total cloud- and rain-water content in the grid column with spatial coordinates (x,y) at time t, the storm advection velocity components along x and y are u and v, respectively, the function $h(x,y,t)$ depends on the microphysical properties of the rain, and the function $S(x,y,t)$ is the rainwater source within the grid column owing to condensation and cloud-to-rainwater conversion. In real-time forecast applications, velocities u and v, and the source function S are based on forecasts by a larger-scale numerical prediction model (e.g. in the US, the ETA model). In addition to the state prognostic equation, two observation equations are typically used:

$$Z_1(x,y,t) = X(x,y,t) + V_1(x,y,t) \qquad (5)$$

and

$$Z_2(x,y,t) = g(x,y,t)\; X(x,y,t) + V_2(x,y,t) \qquad (6)$$

where $Z_1(x,y,t)$ and $Z_2(x,y,t)$ represent the observations of the vertically integrated liquid water content and base-scan rainfall rate, respectively, $g(x,y,t)$ is a function to compute rainfall rate at the base-scan level from the model state $X(x,y,t)$, and $V_1(x,y,t)$ and $V_2(x,y,t)$ are observation errors with statistical properties which are assumed to be known (e.g. French *et al*. 1995).

With the assumption of an exponential drop-size distribution for precipitating particles, the precipitation rate functions at cloud base $h(x,y,t)$ and at ground level $g(x,y,t)$ are expressed as non-linear functions of the dimensionless numbers N_v and N_D, and of the normalized terminal hydrometeor velocity v_T (Georgakakos & Bras 1984*a*). The expressions for the dimensionless updraft-strength number N_v, the sub-cloud-evaporation-strength number N_D, and v_T are

$$N_v = \frac{w_a}{\gamma\ D_a}\ ;\ N_D = \frac{D^o}{D_a}\ ;\ v_T = \gamma \cdot D_a \tag{7}$$

where w_a is the updraft velocity, γ is the gradient of the terminal velocity of hydrometeors with respect to diameter, D_a is the average hydrometeor diameter, and D^o is the cloud-base diameter of the hydrometeor that evaporates completely when it reaches ground level. D^o is given as a function of the atmospheric state of the sub-cloud layer (Georgakakos & Bras 1984*a*).

The storm inflow source term S of Equation (4) is a function of the state of the moist area in the storm environment and of the updraft velocity. The updraft velocity w_a consists of a convective component w_c and an orographic enhancement component w_o. The former is expressed as a function of the available convective potential energy, E_c, of the moist inflow air of the storm according to

$$w_c = \varepsilon_c \cdot \sqrt{2E_c} \tag{8}$$

where ε_c is a parameter accounting for momentum losses due to mixing between the updraft columns and the environment (Georgakakos & Krajewski 1996).

For applications when the updraft velocities are initiated or enhanced by the presence of mountains (orographic enhancement), the vertical component of the orographic three-dimensional velocity field constitutes w_o. The velocity field over mountainous terrain may be obtained by the application of potential-theory flow (Georgakakos *et al.* 1999). For the meso-scale domain of interest, the atmospheric flow is assumed to be irrotational, and characterized by an 850-mbar wind vector. We specify the velocity potential $\varphi(x,y,z)$ as

$$\varphi(x,y,z) = U(x) + Z(z)Y(y)X(x) \tag{9}$$

where U, Z, Y and X are functions to be determined, and x, y and z are the independent spatial variables, with x being the wind vector direction. Function $\varphi(.)$ is the solution to the following boundary value problem:

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + \frac{\partial^2\varphi}{\partial z^2} = 0 \tag{10}$$

where the Neumann boundary conditions specify that the directional spatial derivatives vanish at the domain boundaries, except at the lower boundary, for which

$$\frac{\partial\varphi}{\partial z} = u_o \frac{\partial s}{\partial x} \tag{11}$$

In Equation (11), $\partial s/\partial x$ represents the topographic gradient function, and u_o is the free-stream velocity component along the x axis.

A recent operational field application

The goal of the subject application was to design, implement and test a prototype software system for the operational estimation and prediction of rainfall and stream-flow in the sub-catchment areas of the Panama Canal watershed in Panama. The available operational data in the watershed include 15-min weather radar reflectivity, hourly rainfall, discharge and surface weather reports from telemetered rain-gauges (ALERT), upper-air radiosonde observations from weather balloons launched twice daily, and twice-daily ETA model forecasts produced for North America by the US National Weather Service. The Panama Canal watershed is over mountainous terrain with a distinct rainy season. This project was performed under the auspices of the International Technology Transfer Center of the Office of Hydrology, National Weather Service, NOAA. In addition to collaborating with the staff of the Panama Canal Authority (PCA), HRC collaborated with (a) a private-sector company (Riverside Technology, Inc.), which was responsible for implementing the NWSRFS at PCA, and (b) with the University of Iowa, Iowa Institute of Hydraulic Research, which was responsible for developing bias removal procedures for the Panama radar data. HRC staff developed the precipitation estimation and forecast component PANMAP, and calibrated the state estimator in SS-SAC (see above) for application to the Panama Canal watershed.

The watershed was divided into 11 sub-catchment areas, and mean areal rainfall estimates and forecasts were produced for each of these sub-catchment areas over a 12-h prediction horizon with hourly resolution. The predictions were input to the state-space form of the Sacramento hydrological model coupled with a linear routing model, and stream-flow forecasts were obtained for ten stream gauge sites and lake inflow sites in the watershed.

For the first time, apparently, the components of the integrated forecast software developed include: data ingest and quality control components, including a ground clutter and bias removal component for radar data; a mean areal rainfall estimation component for sub-catchments using radar and rain-gauge rainfall data, and with estimates of associated error variances; an orographic updraft enhancement component using potential theory flow concepts; the state-space form of a convective-rainfall prediction model suitable for tropical convection and with the capability of generating forecast error variances in real time; the state-space form of the Sacramento rainfall-runoff model coupled to a linear reservoir routing model; and computer graphics components. To avoid excessive real-time computations, the potential vertical velocity field was pre-computed for several 850-mbar wind directions and magnitudes, and the results were tabulated for real-time use. Georgakakos *et al*. (1999) and Sperfslage *et al*. (1999, 2000) describe the operational-system design and component function in detail.

Tests of the various components with limited initial data showed that the system is able to work with a variety of data configuration scenarios, and good short-term predictions of rainfall and stream-flow have been obtained with historical hourly data (Figures 2 and 3). The system was found to be suitable for real-time implementation and testing by the PCA, where it has been used in an operational environment since October 1998.

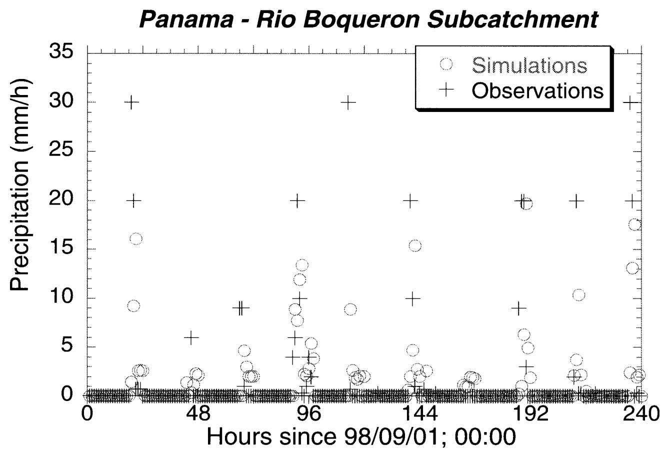

Figure 2 | Observations and real-time forecasts of hourly mean areal rainfall for the Rio Boqueron sub-catchment in Panama using only persisted surface meteorological data.

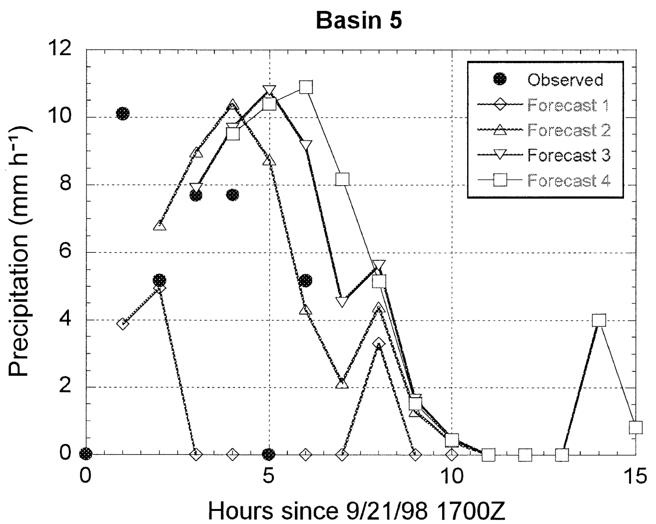

Figure 3 | Observations and real-time forecasts of hourly mean areal rainfall for a Rio Chagres sub-catchment in Panama using ETA meteorological forcing. The maximum forecast lead-time is 12 h, and several forecast preparation times are shown.

Issues

The system implemented by the Panama Canal Authority is a prototype synthesis based on well-tested research products. As such, it presented the developers and users with unique technology transfer issues.

The training of field personnel on the theory and practice of the components of the prototype system was an important prerequisite of the effective use of the operational system. The complexity of the system requires training in meteorology, hydrology and stochastic process theory, while its implementation requires a working knowledge of real-time operations including data-collection from various hydrometeorological sensors. The presence of both meteorologists and hydrologists within the PCA branch responsible for the operation of the system greatly facilitated the reciprocal technology transfer activities.

The design of the system to allow a variety of probable data input scenarios was one important activity that contributed toward good operational system performance. Because the system relies on several means of communication of varying reliability to acquire real-time data (e.g. Sperfslage *et al*. 2000), it runs for a non-negligible fraction of its operational time with a subset of the data required for full component utilization. This necessitated a modification of the nominal system configuration, and a formulation of the state estimator to allow for a variety of input data scenarios and for continuity in forecast and update variances for different configurations of the input uncertainty covariance matrices.

The multidisciplinary nature of the system also necessitated the establishment of new operational protocols within the Panama Canal Authority that allowed for a close collaboration between meteorologists and hydrologists on a day-to-day basis. To facilitate these activities, the system output was designed to provide the user with a wealth of meteorological information which is either input to, or computed by, the system (e.g. ETA convective available potential energy forecasts, hydrometeor size distributions, rainfall abstractions due to sub-cloud evaporation, etc.).

The development of the precipitation forecast component of the Panama Canal watershed forecast system offered HRC staff many opportunities for research. Post-doctoral associates in hydrometeorology developed orographic enhancement models for updraft velocities based on spatial and upper-air data from the geographic information system (GIS) to study the climatology of the updraft field over Panama. Engineering staff designed robust state estimators suitable for model-input covariances with time-varying composition, and the necessarily complex system design and implementation were fruitful training activities.

Perhaps the most significant on-going activity for this operational application is the monitoring and evaluation of system performance in real time. This will lead to the subsequent determination of necessary system improvements.

CONCLUSIONS AND PROSPECTS

The following conclusions were reached on the basis of the technology transfer examples discussed here and from other HRC experience.

1. Sustainable corporate technology transfer from basic research to an operational environment is feasible in hydrometeorology when performed by organizations that have a long-term technology transfer mission and possess the appropriate research and training capabilities.
2. Successful technology transfer provides (a) significant and necessary improvements to current field operations, and (b) valuable experience and research directions for post-doctoral and other scientific and engineering personnel.
3. A significant reciprocal training component between the developers and the users in the field must accompany all technology transfer activities in order to achieve a successful end product.
4. Technology transfer in the field of hydrometeorology must accommodate large natural uncertainties, and a significant effort must be put into uncertainty modelling and robust system design in view of the variety of the data required and the varying reliability of the means of data acquisition.

Some of the significant challenges facing those practicing corporate technology transfer in hydrometeorology are listed below.

1. It will be necessary to strengthen ties with the university faculty concerned in an era when the ratio

of reward versus time spent is low in the academic environment.

2. There should be a stable and balanced group of core staff in the technology transfer organization in order to ensure continuity in the productive research performed by transient post-doctoral associate staff. This core group should represent diverse disciplines, and be capable of interdisciplinary research, development and implementation activities.
3. New forms of contracting for technology transfer should be developed, since this activity does not fit well under the present grant or contract classifications and requirements. Cooperative agreements with government organizations to establish demonstration projects seem to be the most promising method.
4. It will be necessary to develop a mutually beneficial protocol to facilitate the collaboration of non-profit-making technology-transfer organizations with private sector for-profit companies for enhanced and sustainable technology transfer. The organization of national and international workshops in this area would establish communication lines and develop methods of ensuring sustainable financial and copyright agreements.

ACKNOWLEDGEMENTS

I am grateful to the HRC staff for their many and varied contributions to the material from which this article was drawn. The references identify them. I am also indebted to Witold Krajewski and Anastasios Tsonis, members of the HRC Board of Directors, for encouraging and supporting HRC's technology transfer program since its establishment in 1994. The particular technology transfer applications mentioned here were funded over a period of several years by the Office of Hydrology, US National Weather Service, NOAA, by the US National Science Foundation, by the US Bureau of Reclamation, and by NASA. Michael Hudlow, Dan Fread, George Smith, Eric Anderson, Michael Smith, Rob Hartman, Eric Stremm, Curt Barrett, Bob Jubach, Giny Galvin, Bill Pennington, David Reed, David Bowles, Carlos Vargas and the staff of the Meteorological and Hydrological Branch of the Panama Canal Authority provided valuable assistance in many aspects of the technology transfer process. The opinions expressed herein are those of the author and do not necessarily express the views of the US Federal Government Agencies mentioned. This paper is based on the keynote address given by the author at the Hydroinformatics 2000 International Conference organized by the Iowa Institute of Hydraulic Research in Cedar Rapids, Iowa, 23–27 July 2000 (IIHR, 2000).

REFERENCES

Bae, D. H., Georgakakos, K. P. & Nanda, S. K. 1995 Operational forecasting with real-time databases. *ASCE J. Hydraul. Div.* **121**(1), 49–60.

Bras, R. L. & Rodriguez-Iturbe, I. 1985 *Random Functions and Hydrology*. Addison-Wesley, Reading, MA, 559 pp.

Dolcine, L., Andrieu, H. and French, M. N. 1998 Evaluation of a conceptual rainfall forecasting model from observed and simulated rain events. *Hydrol. Earth Syst. Sci.* **2**(2–3), 173–182.

Ettema, R. & Kennedy, J. F. 1990 Commercial projects at university laboratories. Student training? Research adjunct? Or unfair competition? *IAHR Bull.* **7**(2), 13–18.

French, M. N. & Krajewski, W. F. 1994 A model for real-time quantitative rainfall forecasting using remote sensing. 1. Formulation. *Water Resour. Res.* **30**(4), 1075–1083.

French, M. N., Andrieu, H. & Krajewski, W. F. 1995 Radar reflectivity observation error and the moments of vertically integrated liquid water content. *J. Atmos. Ocean. Technol.* **12**(2), 404–409.

Gelb, A. (ed.) 1974 *Applied Optimal Estimation*. MIT Press, Cambridge, MA, 374 pp.

Georgakakos, K. P. 1986*a* A generalized stochastic hydrometeorological model for flood and flash-flood forecasting. 1. Formulation. *Water Resour. Res.* **22**(13), 2083–2095.

Georgakakos, K. P. 1986*b* A generalized stochastic hydrometeorological model for flood and flash-flood forecasting. 2. Case studies. *Water Resour. Res.* **22**(13), 2096–2106.

Georgakakos, K. P. 1987 Real-time flash flood prediction. *J. Geophys. Res.* **92**(D8), 9615–9629.

Georgakakos, K. P. 1994 Key developments in operational flood prediction. *Report on the Proceedings of a US–Spain Bilateral Workshop on Natural Hazards*. Barcelona, 8–11 June 1993 (ed. J. Corominas & K. P. Georgakakos), pp. 120–143. Iowa

Institute of Hydraulic Research, University of Iowa, Iowa City, IA.
Georgakakos, K. P. 1995 On the establishment of a US National Center for Hydrologic Research and Technology Transfer. *J. Hydrol.* **172**, 15–21.
Georgakakos, K. P. 2000 Covariance propagation and updating in the context of real-time radar data assimilation by QPF models. *J. Hydrol.* **239**, 115–129.
Georgakakos, K. P. & Bras, R. L. 1982 Real-time, statistically linearized, adaptive flood routing. *Water Resour. Res.* **18**(3), 513–524.
Georgakakos, K. P. & Bras, R. L. 1984*a* A hydrologically useful station precipitation model. 1. Formulation. *Water Resour. Res.* **20**(11), 1585–1596.
Georgakakos, K. P. & Bras, R. L. 1984*b* A hydrologically useful station precipitation model. 2. Case studies. *Water Resour. Res.* **20**(11), 1597–1610.
Georgakakos, K. P. & Foufoula-Georgiou, E. 1991 Real-time coupling of hydrologic and meteorological models for flood forecasting. In *Recent Advances in the Modeling of Hydrologic Systems* (ed. D. S. Bowles & P. E. O'Connell), pp. 169–184. Kluwer Academic, Boston, MA.
Georgakakos, K. P. & Hudlow, M. D. 1984 Quantitative precipitation forecast techniques for use in hydrologic forecasting. *Bull. AMS* **65**(11), 1186–1200.
Georgakakos, K. P. & Krajewski, W. F. 1996 Statistical–microphysical causes of rainfall variability in the tropics. *J. Geophys. Res.* **101**(D21), 26165–26180.
Georgakakos, K. P. & Smith, G. F. 1990 On improved operational hydrologic forecasting: results from a WMO real-time forecasting experiment. *J. Hydrol.* **114**, 17–45.
Georgakakos, K. P. & Sperfslage, J. A. 1995 *Hydrologic Forecast System—HFS: A User's Manual. HRC TN 1.* Hydrologic Research Center, San Diego, CA, 17 pp.
Georgakakos, K. P., Rajaram, H. & Li, S. G. 1988 *On improved operational hydrologic forecasting of streamflows. IIHR Report 325.* Iowa Institute of Hydraulic Research, University of Iowa, IA, 162 pp.
Georgakakos, K. P., Sperfslage, J. A., Tsintikidis, D., Carpenter, T. M., Krajewski, W. F. and Kruger, A. 1999 *Design and Tests of an Integrated Hydrometeorological Forecast System for the Operational Estimation and Forecasting of Rainfall and Streamflow in the Mountainous Panama Canal Watershed. HRC TR 2.* Hydrologic Research Center, San Diego, CA, 143 pp.
Grecu, M. 1999 Use of radar data in short-term quantitative forecasting. *PhD thesis,* Department of Civil and Environmental Engineering, University of Iowa, Iowa City, IA.
IIHR (Iowa Institute of Hydraulic Research) 2000 *Fourth International Conference on HydroInformatics, 23–27 July 2000. Abstract Volume and Proceedings on CD-ROM.* Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, IA.
Kitanidis, P. K. & Bras, R. L. 1980*a* Real-time forecasting with a conceptual hydrologic model. 1. Analysis of uncertainty. *Water Resour. Res.* **16**(6), 1025–1033.
Kitanidis, P. K. & Bras, R. L. 1980*b* Real-time forecasting with a conceptual hydrologic model. 2. Applications and results. *Water Resour. Res.***16**(6), 1034–1044.
Krzysztofowicz, R. 1983 Why should a forecaster and a decision maker use Bayes theorem? *Water Resour. Res.* **19**(2), 327–336.
Lee, T. H. & Georgakakos, K. P. 1990 A two-dimensional stochastic–dynamical quantitative precipitation forecasting model. *J. Geophys. Res.* **95**(D3), 2113–2126.
Lee, T. H. & Georgakakos, K. P. 1996 Operational rainfall prediction on meso-g scales for hydrologic applications. *Water Resour. Res.* **32**(4), 987–1003.
Loucks, D. P. (ed.) 1989 *Closing the Gap Between Theory and Practice. IAHS Publication No. 180.* IAHS Press, Institute of Hydrology, Wallingford, UK, 303 pp.
Mesinger, F. 1996 Improvements in quantitative precipitation forecasts with the ETA regional model at the National Centers for Environmental Prediction. The 48-km upgrade. *Bull. AMS* **77**(11), 2637–2649.
NOAA-Video 1999 Sacramento soil-moisture accounting model calibration. Demonstration of an interactive approach. *VHS Training Video Series Produced by HRC.* Office of Hydrology, NWS-NOAA, Silver Spring, MD, 5.25 hours.
NRC (National Research Council) 1991 *Opportunities in the Hydrologic Sciences*. National Academy Press, Washington, DC, 348 pp.
Pandey, G., Cayan, D. R., Dettinger, M. D. & Georgakakos, K. P. 2000 A hybrid model for interpolating daily precipitation in the Sierra Nevada of California during winter. *AMS J. Hydrometeorol.* **1**(6), 491–506.
Peck, E. L. 1976 *Catchment Modeling and Initial Parameter Estimation for the National Weather Service River Forecast System. NWS HYDRO-31.* NOAA, NWS, Office of Hydrology, Silver Spring, MD.
Rajaram, H. & Georgakakos, K. P. 1989 Recursive parameter estimation of hydrologic models. *Water Resour. Res.* **25**(2), 281–294.
Sperfslage, J. A. & Georgakakos, K. P. 1996 *Implementation and Testing of the HFS Operation as Part of the National Weather Service River Forecast System. HRC TR 1.* Hydrologic Research Center, San Diego, CA, 213 pp.
Sperfslage, J. A., Georgakakos, K. P., Tsintikidis, D., Kruger, A. & Krajewski, W. F. 1999 *PANMAP v. 1.0.1 User's Guide. HRC LDR 10.* Hydrologic Research Center, San Diego, CA, 69 pp.
Sperfslage, J. A., Georgakakos, K. P., Krajewski, W. F. & Kruger, A. 2000 Design and implementation of the Panama mean areal precipitation (PANMAP) forecast system. *Presented at the HydroInformatics 2000 Conference, 23–27 July 2000, IIHR.* University of Iowa, Iowa City, IA, 7 pp.
Waggoner, P. E. (ed.) 1990 *Climate Change and US Water Resources*. Wiley, New York, 496 pp.
World Meteorological Organization (WMO) 1992 Simulated real-time intercomparison of hydrological models. *WMO No. 779* (*Operational Hydrology Report No. 38*). Secretariat of the World Meteorological Organization, Geneva, 241 pp.