APPLICATION OF REMOTE SENSING IN HYDROLOGY *(Proceedings of the Second International Workshop, NHRI Symposium No. 14, October, 1994) NHRI, Saskatoon.*

SATELLITE BASED DISTRIBUTED MONITORING, FORECASTING, AND SIMULATION (MFS) SYSTEM FOR THE NILE RIVER

V. Koren[1]
Riverside Technology Inc.
Denver, CO
and
C. B. Barrett
NOAA/NWS/OH/MFS Project
Silver Spring, MD

ABSTRACT

Currently the National Oceanic and Atmospheric Administration (NOAA) is in process of developing a river forecast system for the Nile river. This Monitoring, Forecasting and Simulation project is funded by the U.S. Agency for International Development and the executing agency is the United Nations Food and Agriculture Organization (FAO). The prime objective of the MFS project is to predict the inflow into the High Aswan Dam with as much lead time as possible. An additional goal is to regionalize forecast capability so that many of the ten Nilotic countries within the Nile basin could benefit from use of the Nile river forecasts.

Because of the lack of adequate hydrometeorological data, the METEOSAT data was utilized to obtain more detailed spatial resolution of the distribution of precipitation over the basin. A distributed hydrologic system was designed to take advantage of the satellite derived precipitation as well as known physical characteristics of the river basin from GIS.

Phase I of the project (September 1990-September 1993) involved initial development of a Nile Forecasting System (NFS) for the Blue Nile River. Over 80 percent of the runoff of the Nile originates from the Blue Nile System. Phase I was completed with the installation of the latest version of the NFS in July, 1993. Underway now is Phase II (September 1993-September 1995) which involves significant improvement of the accuracy and simulation of the NFS for the Blue Nile as well as expansion of the system to include the White Nile system. Version 2.1 of the NFS was installed in Cairo in June 1994 and contains enhanced satellite calibration coefficients, a hydrologic calibration system, an enhanced reservoir operation system for the Blue Nile, an improved data assimilator and graphics outputs.

[1] Contact address: NOAA/NWS/OH/Nile Project, 1325 East-West Highway, Silver Spring, MD 20910, U.S.A.

INTRODUCTION

A project to monitor, forecast and simulate (MFS) flows along the Nile river was initiated three years ago. The primary goal of the MFS project is to develop a hydrometeorological forecast system to predict the Nile river flows into the High Aswan Dam with as much lead time as technically feasible. Operation of the Nile irrigation delivery system in Egypt, including its many water control structures and strategies of water use, requires a real-time forecasting system. An additional goal is to regionalize forecast capability so that many of the ten Nilotic countries within the Nile Basin could benefit from use of the Nile river forecasts.

Limited hydrometeorological data are available for the Nile basin. In addition, there are large orographic gradients in both precipitation and potential evaporation. The climate regime varies across a wide range from rain forest to desert. In view of the limited data and the need to account carefully for the orography, it seemed essential to keep the hydrologic models as physically based as possible, to avoid making any unnecessary assumptions and to limit the number of model parameters. In view of the great heterogeneity of climate and orography it was decided to develop a macro-scale distributed system that would permit more physically based use of geographical information. The METEOSAT satellite data were utilized as a tool to obtain more detailed spatial resolution of the distribution of precipitation over the basin.

In Phase I of the Project, September 1990 - September 1993, a distributed system was developed for the Blue Nile basin because over 80 percent of the runoff at Aswan originates from the Blue Nile system. Monthly runoff from the White Nile basin was predicted using stochastic model for Malakal. In order to produce long range flow projections three-five months ahead, the Extended Streamflow Prediction (ESP) technique of the National Weather Service River Forecast System (NWSRFS) was applied.

The first version of the MFS system was installed in 1992 in Cairo. Since then, various enhanced or improved versions have been installed with the latest system installed in June 1994. The first operational forecast for the Nile basin was issued in July 1993. Predicted inflow into the High Aswan Dam five months ahead was very close to observed volumes. Continued planned improvements to the MFS include expansion of the distributed system to the White Nile, development of a Quantitative Precipitation Forecasting (QPF) technique, and the integration of an Aswan Dam decision making/control model with the NFS which will provide the basis for optimal use and distribution of inflow to agriculture and hydropower users.

THE MFS SYSTEM STRUCTURE

The MFS system consists of two subsystems: the Primary Data User System (PDUS) which provides the continuous input of METEOSAT satellite imagery data, and the Nile Forecasting System (NFS) which resides on IBM RISC 6000 workstations. The NFS contains hydrologic models and software required to produce river and flow forecasts along the Nile river.

Real-time METEOSAT satellite imagery data is received every 30 minutes by the PDUS. Imagery data are automatically transferred by Ethernet to the RISC workstations. The NFS then processes the imagery data with the final output being flow hydrographs at designated locations along the Nile river. Once a day the automatic pipeline processes all real-time data, executes all the program runs, updates forecast information, and produces up to date flow simulations for ten locations along the Blue and Main Nile. The computation of data and forecasts are based on the METEOSAT grid which is a quasi-rectangular 5.5 Km grid scale. The user can activate or deactivate any MFS component through the menu system (Barrett, 1993).

The NFS consists of a hydroclimate data base, a preprocessor component, a forecast component, a user interface, and a geographical information system (GIS). Figure 1 shows a schematic of the version 2.1 system.

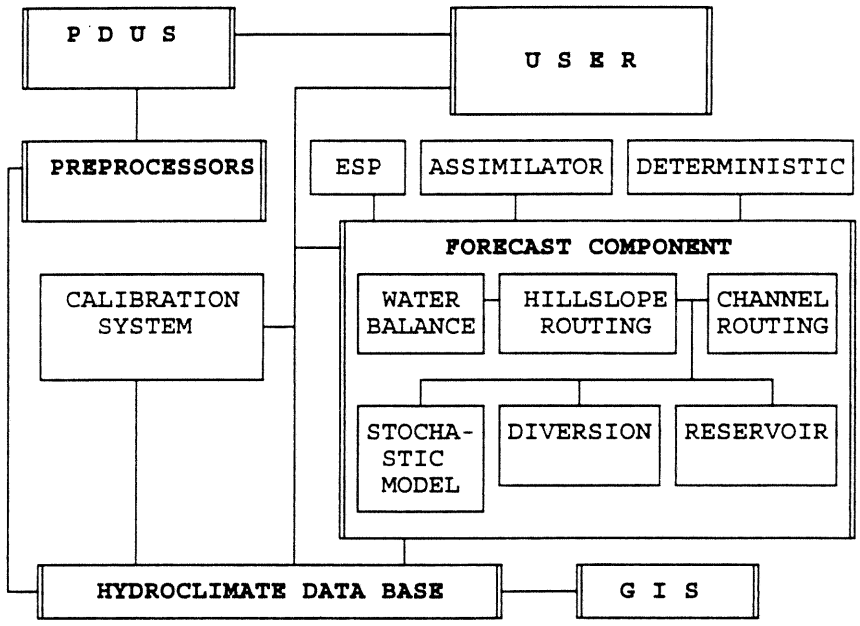

Figure 1. The MFS system version 2.1.

HYDROCLIMATE DATA BASE

The hydroclimate component consists of an observed precipitation time series, climate gridded files of monthly precipitation and potential evaporation data, time series files of observed flow, stage, reservoir elevation, and releases, gridded files of monthly precipitation for more than 50 years and daily precipitation for the last six years, and a METEOSAT raw imagery data base.

Observed precipitation data is automatically input into the NFS via the Meteorological Data Distribution System installed at the Nile Forecast Center in Cairo. In addition, river stage, flow, and reservoir data is manually entered into the system daily. Monthly and daily climate rainfall statistics for every grid cell have been calculated and stored in the data base for the Nile system.

THE PREPROCESSOR COMPONENT

The principle job of the preprocessor component of the NFS is to convert incoming hydrometeorological raw source data into precipitation estimates required by hydrologic models to produce simulations and forecasts. METEOSAT imagery data are automatically entered into a designated directory on the work station via Ethernet from software supplied by the vendor. An automatic sequencing of all the processors occurs once a day in the evening.

The MFS system is unique because very little observed precipitation data are available in the Nile basin. Therefore, a major source of rainfall data becomes satellite estimates at the METEOSAT grid resolution. The preprocessor quality controls half-hourly imagery data, converts imagery data to estimates of rainfall, filters high frequency noise from the precipitation estimate, and merges the satellite estimate data with observed precipitation analysis.

Initially, the project investigated the use of existing satellite precipitation estimation techniques developed by Reading University/U.K., Bristol University/U.K., GOES Precipitation Index developed by Arkin, the Progressive Refinement Technique as well as the Convective Stratiform Technique (CST) (Newby, 1992). By early 1993 a unique Hybrid Climatological Technique was developed (Schaake, Newby, 1993) which uses cold cloud duration data for different temperature thresholds. Analogues gridded fields are created using raingauge data only. Observed daily precipitation is interpolated using optimal statistical interpolation that takes into account the probability of zero rain, the skewed distribution of rain on rainy days, and the spatial correlation structure of the rain (Schaake, 1993). Because both satellite and gauge only analyses are noisy, the forecast component uses a merged gridded fields as weighted values of both fields for each pixel. In the operational version the preliminary weight factor is a constant and the forecaster can change it. New objective procedures are being developed to determine the 'best' merged estimates.

The gridded merged rainfall estimates are written to the data base that will be used by the forecast component to compute runoff and to do hydrometeorological analysis. A mean areal precipitation time series is also available for preselected subareas.

THE FORECAST COMPONENT

The forecast component consists of hydrologic models and software to produce flow and stage hydrographs based on inputs supplied by the preprocessor (Koren, Schaake, Barrett, 1992). There are a number of hydrologic operations in the version 2.1. These operations consist of a distributed rainfall-runoff model, a reach routing model, a reservoir operation component, a stochastic model, a long-term flow prediction technique (ESP), a data assimilation to filter rainfall inputs and state variables, and a model calibration system.

The Hydrologic Models

The distributed rainfall-runoff model is a grid point model with the sub-basin represented as connected grid points with each grid cell being a METEOSAT pixel. It consists of a water

balance model developed by Koren and Schaake (1992) which produces surface and sub-surface runoff, a hillslope routing model to route surface and subsurface runoff within the cell to the stream, and a channel routing model to move water from grid cell to grid cell.

The water balance model is based on two-layer structure. The thin upper layer represents short-term retention of storm water. Precipitation and potential evaporation is input of this layer, and excess precipitation, P_x, and actual evapotranspiration is output. Precipitation infiltrates into this layer until its water storage capacity is filled. The excess precipitation is input into the bottom layer. The bottom layer has larger storage and can store a lot of excess precipitation. Evaporation from this layer is a linear function of its soil moisture deficit, D, and it takes place only when there is not enough water to evaporate from the upper layer. Subsurface runoff is also a linear function of soil moisture content of the bottom layer. Surface runoff, q_s, equation is based on the Soil Conservation Service Curve Number formula (SCS, 1972). Moore (1987) has showed that this equation accounts for the sub-grid spatial variability of rainfall and soil absorption capacity under the assumption of exponential distribution of rainfall and capacity over the area. The equation was modified to be able simulate runoff by different time steps. Based on physical concepts, the smaller time step is used, the thinner soil layer affects on the infiltration rate, the equation was modified to:

$$q_s = \frac{P_x}{P_x + D_{eff}} * P_x \qquad (1)$$

where D_{eff} is an effective soil moisture deficit that depends on time step, dt, and soil moisture content of the bottom layer

$$D_{eff} = D * [1 - \exp(-K_{dt}\sqrt{dt})] \qquad (2)$$

where K_{dt} is a parameter.

The hillslope, channel, and reach routing models are based on kinematic wave equation with nonlinear relationships of discharge-storage. An implicit numerical scheme was used for kinematic equation solution.

There are two reservoirs in the Blue Nile basin, Roseires and Sennar, where the reservoir operation component was applied. These reservoirs operate according to fixed rules or phases of operation. In general, the reservoirs will fill storage during the occurrence of the annual summer flood, and spill during the winter months.

A first order Markov stochastic model (Koren, 1993) is used to simulate flows for the White Nile river at Malakal. This model is included to provide the capability of the NFS to predict total inflow into the High Aswan Dam. The model predicts monthly flows for three-five months ahead which are transformed into daily discharges by using a linear recursive procedure.

The Extended Streamflow Prediction (ESP) Technique

The (ESP) produces long-term forecast hydrographs based on past climatological conditions and current soil moisture states in the watershed. During an ESP run, the current soil moisture states are used as the starting point to generate more than 50 years of runoff traces based on previous monthly potential evaporation, and monthly and daily precipitation for the historical record. The resultant projections represent the range of past climatic conditions which are equally likely in the future. ESP then fits the simulated traces to a probability distribution. Expected and 90%, 75%, 25% and 10% excedence probability hydrographs are calculated for selected locations.

Data Assimilation

The purpose of data assimilation is to use near real time discharge data that are observed at several locations to update model state variables and inputs so that the models do a better job of simulating discharge when data are available. Data assimilation also assures the models are in the best possible position to predict future runoff when data are not available. Discrepancies between observed flows and simulated flows are primarily due to errors in precipitation estimation, water balance state variable estimates and channel routing states. The assimilator recognizes these input errors and adjusts daily values to minimize the difference between observed and simulated flows while taking into account possible uncertainties of precipitation and state variables.

Data assimilation is a new area in hydrology. There is practically no experience in distributed model assimilation. Input and output data vary in space and time, and there are many unknowns that need to be solved. On the other hand, the measured data are usually available for a few locations. To reduce the dimension of the problem and noise of point values, averaged variables for the area above an outlet were adjusted. Thus it is possible to use approaches similar to approaches developed for the lumped parameter models, e.g. (Koren, 1984). Precipitation data for the Blue Nile basin do not account for daily fluctuations of flows so time averaging was used to smooth the inputs.

The algorithm is based on minimization of a cost function with constraints:

$$F = F_Q + F_S(\omega_S, K_{S,i}) + F_P(\omega_{P,i}, K_{P,i}) \tag{3}$$

$$K_{P,\min} \le K_{P,i} \le K_{P,\max}$$
$$K_{S,\min} \le K_{S,i} \le K_{S,\max}$$

where F_Q, F_S and F_P are contributions of discharges, state variables and precipitation adjustments into a cost function value respectively, K_P and K_S are correction factors of precipitation and state variables, ω_P and ω_S are weight coefficients that depend on uncertainties of rainfall and state variables (Koren, 1994). The weight coefficient of the state variables was assumed to be constant. The weight coefficients of rainfall vary for different time intervals and from one assimilation to other depending on sensitivity of runoff to rainfall and rainfall estimate errors if they are available.

Model Calibration System

A simple calibration system was linked to a menu driven user interface.The system has some limitations: (1) An automatic calibration utilized on the lumped parameter basis only, (2) The distributed model parameters can be estimated in the nonautomatic mode using trial and error best fit.

The Shuffled Complex Evolution method (SCE) (Duan, Sorooshian, Gupta, 1992) is used for the automatic calibration. The SCE method is able to analyze the criteria surface for a global minimum with a selected range of model parameters. Unlike many other optimization methods, SCE estimates do not depend on initial values of the model parameters. Mean square error of simulated and observed runoff (usually monthly) is used as calibration criteria. The calibration can be run for different time steps simultaneously, e.g., 1, 2, 5 days. Two-days and five-days input data will be calculated using basic input data (daily or monthly). If only monthly rainfall data is available, daily rainfall values will be generated using a disaggregation procedure that uses daily statistics of daily rainfall (Koren, Schaake, 1992).

THE USER INTERFACE

The user interface displays satellite imagery data, gridded data, and time series data; it also serves as the interface between the forecaster and the NFS software, data base and models. The forecaster can run hydrologic forecast runs as well as control the parameterization, re-execution, and backtracking of the standard automatic pipeline run. The user interface is driven by a menu system that is linked to actions through configuration files (Bellerby, 1994).

THE GEOGRAPHICAL INFORMATION SYSTEM (GIS)

The GIS was included in the NFS to create a map background for display purposes as well as to perform analysis to estimate hydrologic model parameters including gridded flow path connectivity, drainage basin area definition for forecast locations, and physical variables such as elevation, slope and length.

The GIS utilizes vector and gridded raster file formats. The raw data were manually digitized from 1:2,000,000 scale topographic maps produced by the U.S. Defense Mapping Agency. A commercial GIS program (ARC/INFO) was used to digitize the basic GIS data sets which included streams, elevations contours, political boundaries, city names, and basin boundaries.

The customized GIS developed for the project addresses important issues such as methods of combining raster and vector data sets, integrating hydrologic models with hydrometeorological and geographic data, and estimating hydrologic parameters with digital geographic data (VanBlargan, 1992).

SYSTEM IMPLEMENTATION AND RESULTS

The Blue Nile and Atbara basins were divided into an identical grid resolution using the METEOSAT grid. Connectivity of the grid points was determined by the GIS, based on both stream network definition and elevation data. Because there is no significant lateral inflow, the Main Nile river from Malakal to the High Aswan Dam was considered as a single channel system with possible abstraction of water. For the hydrologic analysis of input/output data, ten subareas were designated (Fig. 2). Each subarea location has been selected based on hydrologic characteristics, forecast purposes, and availability of real-time gauge data.

The NFS has two modes of operation: (1) the standard pipe line run, and (2) run scenarios in workspace areas. The standard run is triggered automatically each day by the clock. Once all the precipitation data have been received and processed, the model system is executed for all grid point locations. State variables, runoff and carry-over files are updated and new time series are created for the forecast points. The nonstandard workspace run option is available if the forecaster wants to create or run scenarios that are necessary for hydrologic analysis or parameter estimation but does not update the NFS carry-over or state variable files. An example of the run scenario is "what if" conditions based on a variable future precipitation.

Two basic types of outputs from the NFS are available: (1) gridded files of runoff and water balance components over the Blue Nile and Atbara basins, and (2) time series files of streamflow and water balance components for selected forecast points. A display system is available to display both the standard and nonstandard run outputs.

Model Parameter Estimation

The NFS model parameters were estimated by using a combination of automatic and manual trail and error calibration techniques. The water balance model parameters were mainly estimated by using automatic optimization. The routing model parameters were estimated by using GIS data and adjusted later manually based on sensitivity analysis and comparison of simulated and observed hydrographs and lag times for the main outlets using daily data for the recent years.

The water balance model calibration has been done in two stages. The first stage was to estimate parameters for small headwater basins on a lumped basis. The second stage used the first stage results to estimate parameters throughout the Nile basin with the distributed rainfall-runoff model, and then fine-tune them using downstream discharge data for large areas.

Daily and monthly discharge data was available for short periods for a number of stream gauges. Unfortunately, daily precipitation data was available only for the recent years and the period of available daily precipitation data does not overlap the period of daily discharge data. However, there were periods when monthly precipitation data overlapped periods of available discharge data, so monthly data have been used for stage one. Monthly precipitation data was disaggregated into daily based on using distribution functions of daily precipitation (Koren and Schaake, 1992).

1 - High Aswan Dam
2 - Dongala
3 - Melut
4 - Malakal
5 - Khartoum
6 - Sennar Dam
7 - Roseires Dam
8 - Diem
9 - Kesse
10 - Atbara
11 - Jebel Aulia Dam
12 - Khasm el Girba Dam

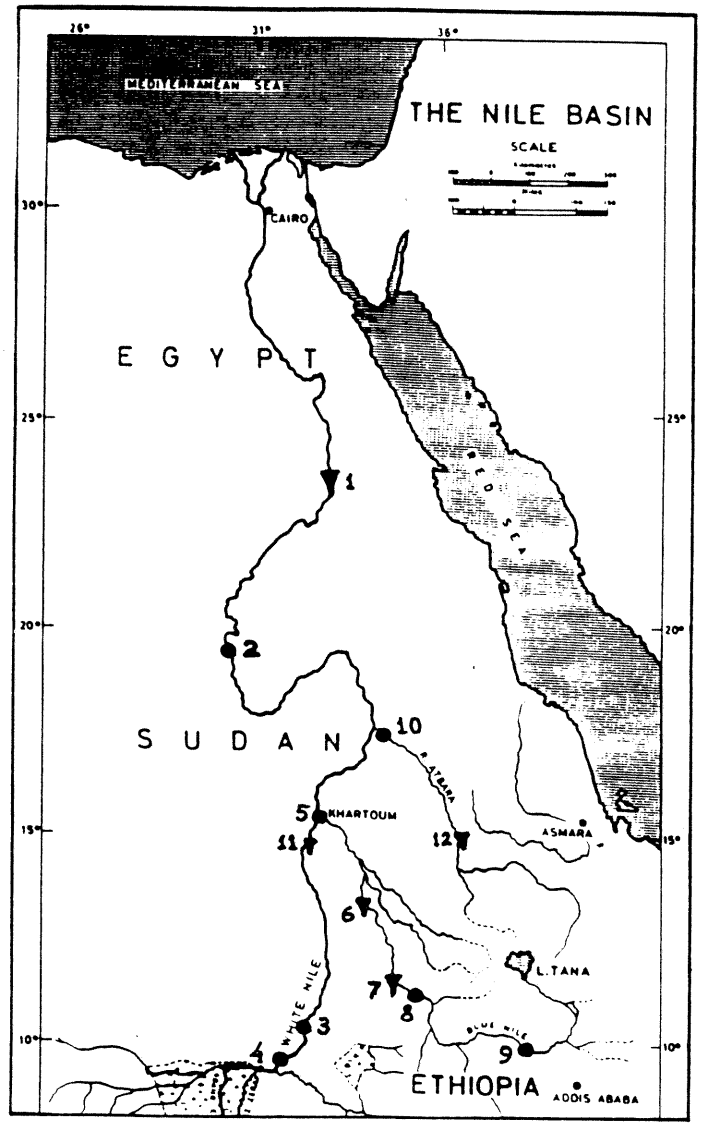

Figure 2. The Nile basin. Major forecast and Control points.

Simulated monthly runoff had an excellent fit for all headwater basins. However, some parameters varied from basin to basin significantly. The variability may depend on uncertainties of input/output data. The periods of available discharge data were very short, and there were only three to five raingauges for the entire 200,000 km^2 area so that parameter estimates may be very noisy. To decrease affect of noise, generalized parameters were obtained by calibrating all headwater basins simultaneously. Mean square errors of monthly runoff simulated using generalized parameters were about twice more than using optimal parameters for each basin, but these errors were close to the errors obtained using optimal parameters and observed rainfall with generated 10% noise. Actual errors of precipitation estimates are also not less than this value. In version 2.1, the generalized parameters for headwater areas were used to initialize parameters for the entire Blue Nile basin.

In the second stage of the calibration, daily gridded precipitation estimates based on gauge-only analysis were used as input to run the distributed model for the entire basin. Hillslope and channel slopes, channel lengths, and pixel areas for each grid cell were calculated using the GIS. Channel roughness coefficients were estimated from geomorphological relationship obtained by analysis of number streams in the U.S. that were similar to those in the Blue Nile basin (Tokar, Johnson, 1993). Channel shape was assumed to be triangular with a constant equal to 2 meters estimated for a few small rivers. The simulated discharges were compared to observed after taking moving averages (usually 5-days) to filter out high frequency 'noise'. Minor adjustments were made to the initial parameters.

The 5-day moving averages of simulated and observed hydrographs at Diem (Sudan Boarder) for four recent years are compared in Figure 3. The accuracy of simulated monthly runoff was very high in comparison to runoff variability. The coefficient of determination of simulated monthly runoff at Diem was 0.85.

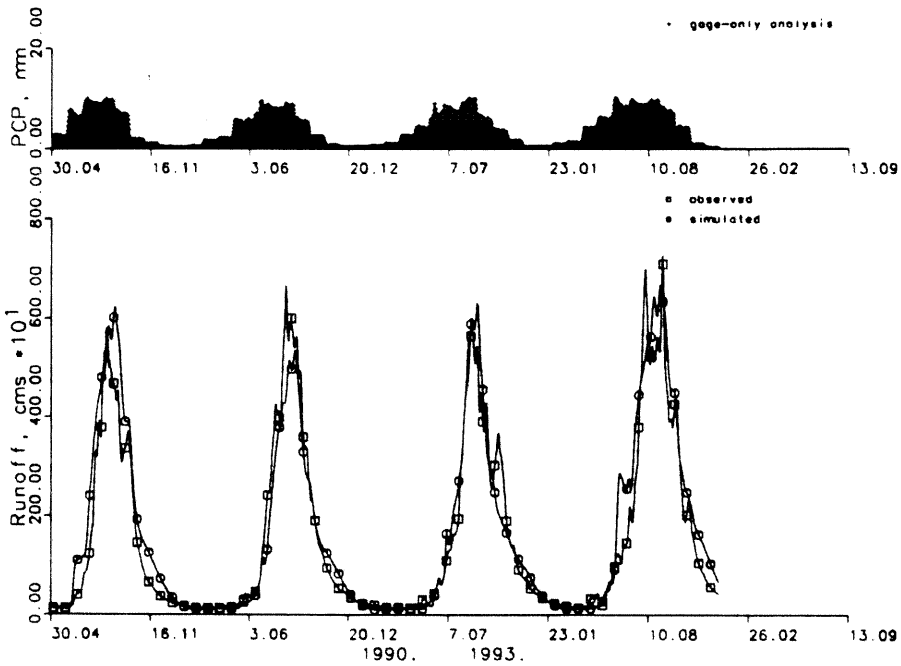

Figure 3. Observed and simulated hydrographs at Diem, the Blue Nile for 1990, 1991, 1992, and 1993 years.

Using Merged Satellite-raingauge Data

Overall a good accuracy of simulated runoff using gauge-only analysis of precipitation was obtained. However, in years where the precipitation is very much above or below normal, the gauge-only analysis, heavily dependents on climatology and available raingauge data, may not do as well, e.g., simulated hydrograph for 1991 year at Diem, Figure 4, was underestimated significantly. There was no observed rainfall data available during the rainy season for this year. Gauge-only analysis in this case will be close to long-term climatological grid. On the other hand, observed runoff was above historical averaged value.

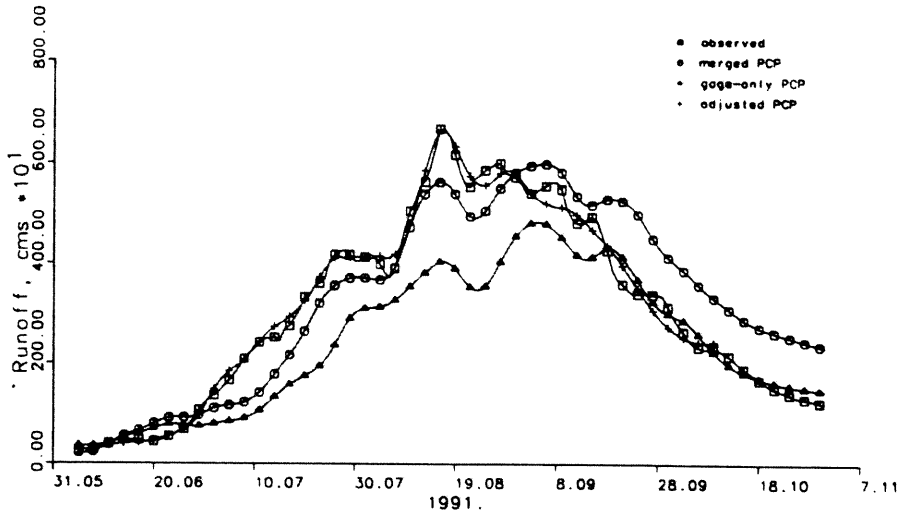

Figure 4. Observed discharges and discharges simulated using gauge-only analysis or merged rainfall, and assimilated discharges at Diem.

A simple weighting method to combine satellite and gauge data has shown an improvement of simulation results. Mean square error of monthly runoff simulated using 0.2 weight for the satellite estimates was 4.63 mm compare to gauge-only input 5.68 mm. As expected, improvement was obtained for 1991, see Figure 4. On the other hand, the adjustment of the model parameters using satellite only data gave significant improvement of simulations, but still mean square error was much higher, 11.8 mm, than using merged or gauge-only precipitation.

Data Assimilation Results

Because satellite and gauge data are noisy and there are model uncertainties, simulated hydrographs differ from observed. Again the hydrograph from 1991 simulated using merged precipitation is still underestimated. The estimated discharges for this year after data assimilation are also plotted in Figure 4. The assimilation was run in a week starting from previously adjusted state variables. A four weeks window with weekly averaging of precipitation was used for assimilation. Clearly the effect of the assimilation is to bring the adjusted discharges into much closer agreement with the observed. Figure 5 shows a comparison of the estimated basin average daily rainfall with the adjusted rainfall resulting from data assimilation. The effect of the adjustment was to increase an average amount of rainfall, and 'reasonable' adjustments were made on individual days considering the accuracy of the daily basin average precipitation estimates.

The ESP Estimates

The ESP benefit depends on a hydrologic system 'memory'. The more 'memory' is available in a river basin the more long-term average runoff may be predicted. An analysis of rainfall-soil moisture-runoff relationships for the Blue Nile showed that runoff for July-September heavily depends on initial soil moisture conditions. This means that there is a rather big 'memory' in the system.

Figure 6 displays cumulative hydrographs at Dongala, inflow point to the High Aswan Dam, of the first operational ESP forecast issued on June 30, 1993. The predicted three months volume was very close to observed runoff that was 17% higher than the long-term average.

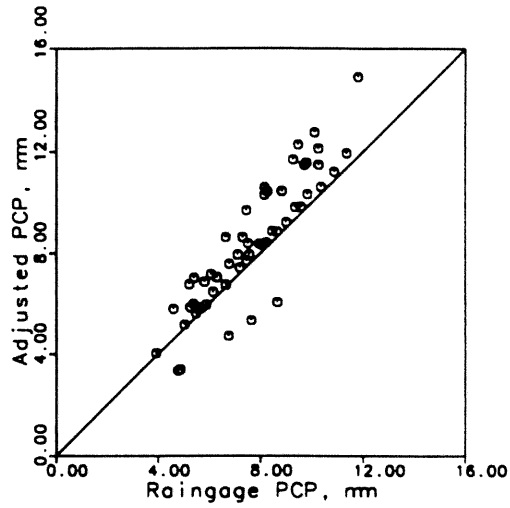

Figure 5. Assimilated daily basin average precipitation vs gauge estimates.

In non-operational mode, the ESP was run for five recent years to predict cumulative runoff for July-September. Mean square errors of simulated volumes at Diem and Dongala were about two times less than variability of observed monthly runoff (Table 1). It means that ESP has a real prediction skill.

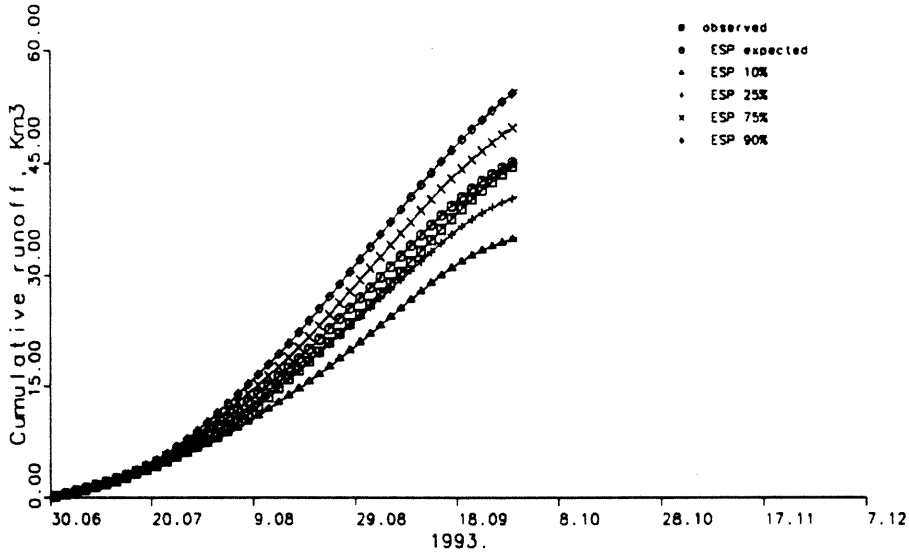

Figure 6. ESP forecast for the High Aswan Dam issued the first week of July, 1993.

Table 1. Mean square errors, S, relative errors, r, standard deviations of observed runoff, S_{obs}, and the coefficient of determination, E, predicted monthly runoff at Diem and Dongala.

Year	Diem				Dongala			
	S	r	S_{obs}	E	S	r	S_{obs}	E
1989	1.64	15	3.08	0.47	0.97	7	5.04	0.21
1990	2.12	24	3.19	0.44	1.54	14	4.94	0.69
1991	1.17	12	3.65	0.68	2.75	23	5.44	0.49
1992	1.13	14	3.42	0.67	3.02	34	4.32	0.30
1993	1.38	15	2.29	0.52	3.10	29	3.82	0.19
Avg	1.53	16	3.26	0.53	2.43	21	4.75	0.49

SUMMARY

The initial operational river forecast system for the Blue Nile River was installed in 1992 in Cairo, Egypt. Since then, various enhanced or improved versions have been installed with the latest system installed in June 1994. The first operational forecast for the Nile was issued in July 1993. The forecast predicted 17% above normal volume inflow into the High Aswan Dam for the period July-November, 1993. The forecast was accurate as observed runoff into the dam approached 17% above normal. However, one can expect that simulated runoff for the extreme years may be under/overestimated because equally likely historical conditions are used for ESP. Including of the Quantitative Precipitation Forecast technique planned for the Phase II will improve ESP in such cases.

Satellite estimates of precipitation can improve runoff simulations, especially when surface observations are very sparse. However, an operational system of satellite estimate adjustment has to benefit from this data.

In addition to operational forecasting, the MFS system can provide helpful information for the water users. Planned integration of a Decision making model into the MFS system will provide the basis for optimal water management.

REFERENCES

Barrett, C.,1993. Monitoring, Forecast, and Simulation System Version 2.0 for the Blue Nile River Basin: User Manual, Nile Project Office, 65 pp.

Bellerby, T. 1994. Nile Forecasting System: System Manual, Monitoring, Forecasting, and Simulation Project Phase, II, 44pp.

Duan, Q., Sorooshian, S. and Gupta, V.K. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. W.R.R., 28(4): 1015-1031.

Koren, V. 1984. Statistical adaptation algorithm in continuous short-range runoff forecasts. Soviet Meteorology and Hydrology, New York, Allerton Press, Inc., 3, pp. 67-70.

Koren, V. and J.C. Schaake. 1992. Daily Water Balance Model and It's Calibration, Nile Technical Note No. 46, 26 pp.

Koren, V., J.C. Schaake and C. Barrett. 1992. Nile River Forecast System Models, Nile Technical Note No. 54, 14pp.

Koren, V. 1993. Forecast Component: Stochastic Model, Nile Technical Note No. 51, 26pp.

Koren, V. 1994. Updating Algorithm and Program (Version 2.1), Nile Technical Note No. 55.21, 12pp.

Moore, R.J. 1987. Towards more effective use of radar data for flood forecasting. In: V.K. Collinge and C. Kirby (eds), Weather Radar and Flood Forecasting, pp. 223-238, J. Wiley.

Newby, J. 1992. Nile Hybrid technique for Version 2.0, Nile Technical Note No. 74, 4 pp.

Schaake, J.C., and Newby J. 1993. Satellite Estimation of Rainfall using the Nile Climatological Method, Nile Technical Note 6.0, 13pp.

Schaake, J.C. 1993. Operational Precipitation Gauge Only Analysis Procedures (NFS Version 2.0), Nile Technical Note 11.4, 18pp.

SCS. 1972. National Engineering Handbook. Section 4, Hydrology. Soil Conservation Service USDA, US Government Printing Office, Washington, DC, USA.

Toxar, A. Sezin, and P. Johnson. 1993. Optimization of River Characteristics in the Blue Nile Watershed. Nile Technical Note No. 121, 6 pp.

VanBlargan, E. 1992. GIS Gridded Connectivity, Nile Technical Note No. 63, 6 pp.