The Role of Monthly Updated Climate Forecasts in Improving Intraseasonal Water Allocation

A. SANKARASUBRAMANIAN

Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina

UPMANU LALL

Department of Earth and Environmental Engineering, Columbia University, New York, New York

NARESH DEVINENI

Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina

SUSAN ESPINUEVA

Philippine Atmospheric, Geophysical and Astronomical Services Administration, Quezon City, Philippines

(Manuscript received 22 September 2008, in final form 4 January 2009)

ABSTRACT

Seasonal streamflow forecasts contingent on climate information are essential for short-term planning (e.g., water allocation) and for setting up contingency measures during extreme years. However, the water allocated based on the climate forecasts issued at the beginning of the season needs to be revised using the updated climate forecasts throughout the season. In this study, reservoir inflow forecasts downscaled from monthly updated precipitation forecasts from ECHAM4.5 forced with "persisted" SSTs were used to improve both seasonal and intraseasonal water allocation during the October–February season for the Angat reservoir, a multipurpose system, in the Philippines. Monthly updated reservoir inflow forecasts are ingested into a reservoir simulation model to allocate water for multiple uses by ensuring a high probability of meeting the end-of-season target storage that is required to meet the summer (March–May) demand. The forecast-based allocation is combined with the observed inflows during the season to estimate storages, spill, and generated hydropower from the system. The performance of the reservoir is compared under three scenarios: forecasts issued at the beginning of the season, monthly updated forecasts during the season, and use of climatological values. Retrospective reservoir analysis shows that the operation of a reservoir by using monthly updated inflow forecasts reduces the spill considerably by increasing the allocation for hydropower during above-normal-inflow years. During below-normal-inflow years, monthly updated streamflow forecasts could be effectively used for ensuring enough water for the summer season by meeting the end-of-season target storage. These analyses suggest the importance of performing experimental reservoir analyses to understand the potential challenges and opportunities in improving seasonal and intraseasonal water allocation by using real-time climate forecasts.

1. Introduction

Recent advances in understanding the linkages between exogenous climatic conditions, such as tropical sea surface temperature (SST) anomalies, and local/regional hydroclimatology offer the scope of predicting the rainfall/streamflow potential on a season-ahead and long-lead (12–18 months) basis (Hamlet and Lettenmaier 1999; Sharma 2000; Piechota et al. 2001; de Souza Filho and Lall 2003). The National Research Council (2002) emphasizes the importance of harnessing this enhanced hydrologic predictability toward potential benefits in water resources system operation. For instance, reservoir rule curves that specify the volume of water to be kept in the reservoir at a particular time of the year to meet the future demand are often obtained based on

Corresponding author address: A. Sankarasubramanian, 2501 Stinson Dr., Box 7908, Raleigh, NC 27695-7908.
E-mail: sankar_arumugam@ncsu.edu

DOI: 10.1175/2009JAMC2122.1

© 2009 American Meteorological Society

the driest envelope in the entire historical record, thereby adhering to the same rule curve every year for reservoir operation. In this regard, a commonly adopted strategy in the United States is to lower the reservoir to a prespecified level every year during the winter to accommodate the upcoming winter and spring peak flows. Several investigators have emphasized the importance of exploiting this improved hydrologic predictability to enhance the management of water and energy systems (Carpenter and Georgakakos 2001; Hamlet et al. 2002; Voisin et al. 2006).

The main intent of this study is to assess the utility of monthly updated probabilistic streamflow forecasts obtained from climate forecasts in improving intraseasonal water allocation. We utilize reservoir inflow forecasts downscaled from monthly updated precipitation forecasts from the ''ECHAM4.5'' general circulation model (GCM) forced with ''persisted'' (i.e., the current anomalous SST conditions are assumed to last over the forecasting period) SSTs (Sankarasubramanian et al. 2008) to improve intraseasonal water allocation and reservoir operation. The reservoir management model adopted here is a simplified version of the dynamic allocation framework reported by Sankarasubramanian et al. (2003). The study site considered is a multipurpose system, Angat reservoir, in the Philippines.

A brief literature review and background on the application of climate forecasts in improving water management is discussed in the next section. Following that, baseline information on Angat basin and its linkage to El Niño–Southern Oscillation (ENSO) is presented. In the next section, we briefly present the monthly updated streamflow forecasts from Sankarasubramanian et al. (2008) along with the formulation of the Angat simulation model. The experimental design used to assess the utility of monthly updated climate forecasts is detailed next along with results and analyses. Last, we summarize the findings of the study along with conclusions.

2. Background

Seasonal forecasts of streamflow could be utilized effectively for multipurpose water allocation and to prepare adequate contingency measures to mitigate hydroclimatic disasters (Lettenmaier and Wood 1993). Recent investigations focusing on the teleconnection between SST conditions and regional/continental hydroclimatology show that interannual and interdecadal variability in exogenous climatic indices modulate the continental-scale rainfall patterns (Ropelewski and Halpert 1987) and streamflow patterns at both global and hemispheric scales (e.g., Dettinger and Diaz 2000) as well as at regional scales (e.g., Piechota and Dracup 1996; Guetter and Georgakakos 1996). In the United States, the National Weather Service River Forecasting System issues 3-month-lead probabilistic forecasts of streamflow for many river basins in the contiguous United States from 12 river forecasting centers using conceptual hydrological models that utilize both land surface conditions (current soil moisture, river, and reservoir conditions) and 3-month-ahead climate forecasts (Schaake and Larsen 1998).

Climate-information-based streamflow forecasts can be obtained using either dynamical or statistical downscaling. The dynamic modeling downscales the large-scale GCM outputs to watershed-scale precipitation and temperature using a regional climate model so that downscaled climate forecasts could be forced with a hydrologic model to develop streamflow forecasts at the desired location (e.g., Leung et al.1999). However, uncertainty propagation from the coupling of these models (Kyriakidis et al. 2001) and conversion of the gridded streamflow/precipitation forecasts into reservoir inflow forecasts pose serious challenges in employing dynamical downscaling for water management applications. The alternate approach—statistical downscaling—basically employs statistical models to downscale GCM outputs to develop streamflow forecasts at a desired location (Gangopadhyay et al. 2005). Studies have also related well-known climatic modes to observed streamflow in a given location using a variety of statistical models ranging from simple regression (e.g., Hamlet and Lettenmaier 1999) to complex methods such as linear discriminant analysis (Piechota et al. 2001), spatial pattern analysis (Sicard et al. 2002), and semiparametric resampling strategies (de Souza Filho and Lall 2003).

Studies have shown that seasonal streamflow forecasts developed using tropical/extratropical climatic and land surface conditions have resulted in improved management of water supply systems (Hamlet and Lettenmaier 1999; Yao and Georgakakos 2001; Hamlet et al. 2002). Using retrospective streamflow forecasts for the Columbia River, Hamlet et al. (2002) have shown that long-lead streamflow forecasts can be effectively utilized in operating reservoirs to obtain increased annual average hydropower. In a similar way, coupled hydraulic–hydrologic prediction models with robust forecast-control methods could also result in increased resiliency of reservoir systems to climate variability and change (Georgakakos et al. 1998). Also, climate-information-based streamflow forecasts could also be effectively utilized for invoking restrictions and proactive water conservation measures during droughts (Golembesky et al. 2009). Studies have also pursued a theoretical approach in understanding the conditions under which seasonal forecasts could be utilized for improving reservoir releases and to meet end-of-season target storage (Georgakakos and Graham 2008).

Though the utility of seasonal climate forecasts in improving water management has been shown in the literature, it is widely acknowledged that numerous challenges/gaps exist in the real-time application of climate forecasts by water managers (Pagano et al. 2001; Hartmann et al. 2002). One main challenge is in developing operational rule curves that could change continuously as the season progresses depending on the updated streamflow potential. Most of the investigations on climate–water applications have primarily used seasonal streamflow forecasts developed contingent on dominant climatic modes for quantifying the improvements on water allocation (Hamlet et al. 2002; Maurer and Lettenmaier 2004; Golembesky et al. 2009). Recent studies on operational streamflow forecast development show that seasonal streamflow forecasts downscaled from monthly updated climate forecasts are very effective in reducing the effects of intraseasonal variability in streamflows (Sankarasubramanian et al. 2008). The main intent of this study is to investigate the utility of streamflow forecasts developed from monthly updated climate forecasts in improving the intraseasonal water allocation for a multipurpose system, the Angat reservoir, in the Philippines.

3. Climate variability and Angat reservoir management

Angat, a multipurpose reservoir in the Philippines with a storage capacity of 850 MCM (1 MCM = 10^6 m^3), is the main source of water for the metropolitan (Metro) Manila supply as well as for irrigation in the Bulacan Province (Figs. 1a,b). Angat watershed, located on the ranges of the Sierra Madre in Bulacan Province, has a catchment area of 568 km^2 with an average annual runoff contributing to 2030 MCM. Angat reservoir, owned by National Power Corporation (NPC), has a rated capacity of 246 MW and also supplies water for two seasons [October–February (ONDJF) and June–September] of irrigation in the Bulacan Province (average ONDJF demand: 385 MCM) and for Metro Manila (average ONDJF demand: 570 MCM). Total hydropower generated from Angat accounts for 16% of the installed hydropower in the Luzon grid. Water supply for irrigation is diverted through the main turbines (rated capacity: 200 MW), and the releases for Metro Manila are utilized for running the auxiliary turbines (rated capacity: 48 MW). Hence, the power generated through the main turbine is proportional to the volume of water released for irrigation, whereas the power generated from auxiliary is proportional to the water released for Metro Manila. Downstream releases from the dam also have to ensure a minimum 2 m^3 s^{-1} for aquatic life protection. Thus, Angat reservoir is primarily a within-year reservoir with a storage-to-annual-demand ratio of 0.38 that is managed with an intent to more efficiently allocate inflows with high seasonal variation.

Water allocation from the Angat reservoir is governed by the National Water Resources Board (NWRB), which convenes monthly to decide about allocation among the three stakeholders (Metro Manila water supply, National Irrigation Administration, and NPC). Figure 1c provides the operational rule curves (upper and lower rule curves) used by NWRB for water allocation from the Angat reservoir along with the recorded storages for some prior years. The upper and lower rule curves depict the total amount of storage that needs to be kept in the reservoir to meet monthly water demand if the monthly inflows correspond to 50% (upper) and 80% (lower) exceedance probabilities of the observed inflows. Thus, the operating policy suggests allocation for all of the three uses if the water level is above the upper rule curve. On the other hand, the allocation for municipal and irrigation demand (no additional water allowed for hydropower generation) would be permissible if the water level in the reservoir is between the upper and lower rule curves. If the water level is below the lower rule curve, then allocation is ensured only for municipal use. The flood rule curves shown in Fig. 1c provide the storage available for flood control. Thus, reservoir operation is primarily guided by the climatological inflow probabilities and also based on the current storage in the reservoir. This could lead to significant system losses (spill) in the reservoir that result in decreased hydropower generation and reduced allocation for municipal and irrigation use. Operation of the reservoir during the 1997–98 ENSO is a clear case of lost opportunity in improving the allocation contingent on climate forecasts.

Figure 1c shows the recorded storages in the Angat reservoir for the period of 1996–2001 along with operational rule curves. From Fig. 1c, we can clearly see that the reservoir storages were below the lower rule curve in 1997, which resulted in abandoning of cropping of northeast-monsoon-season irrigation (October–February). The inflows were below normal because of El Niño conditions in the tropical Pacific Ocean that continued until September 1998. Owing to this fact, reservoir levels never went above the lower rule curves, resulting in no irrigation during the southwest-monsoon season (June–September). The lowest-ever recorded water level in Angat was 158.15 MSL on 18 September 1998. Thus, NWRB had to make a decision in terms of water

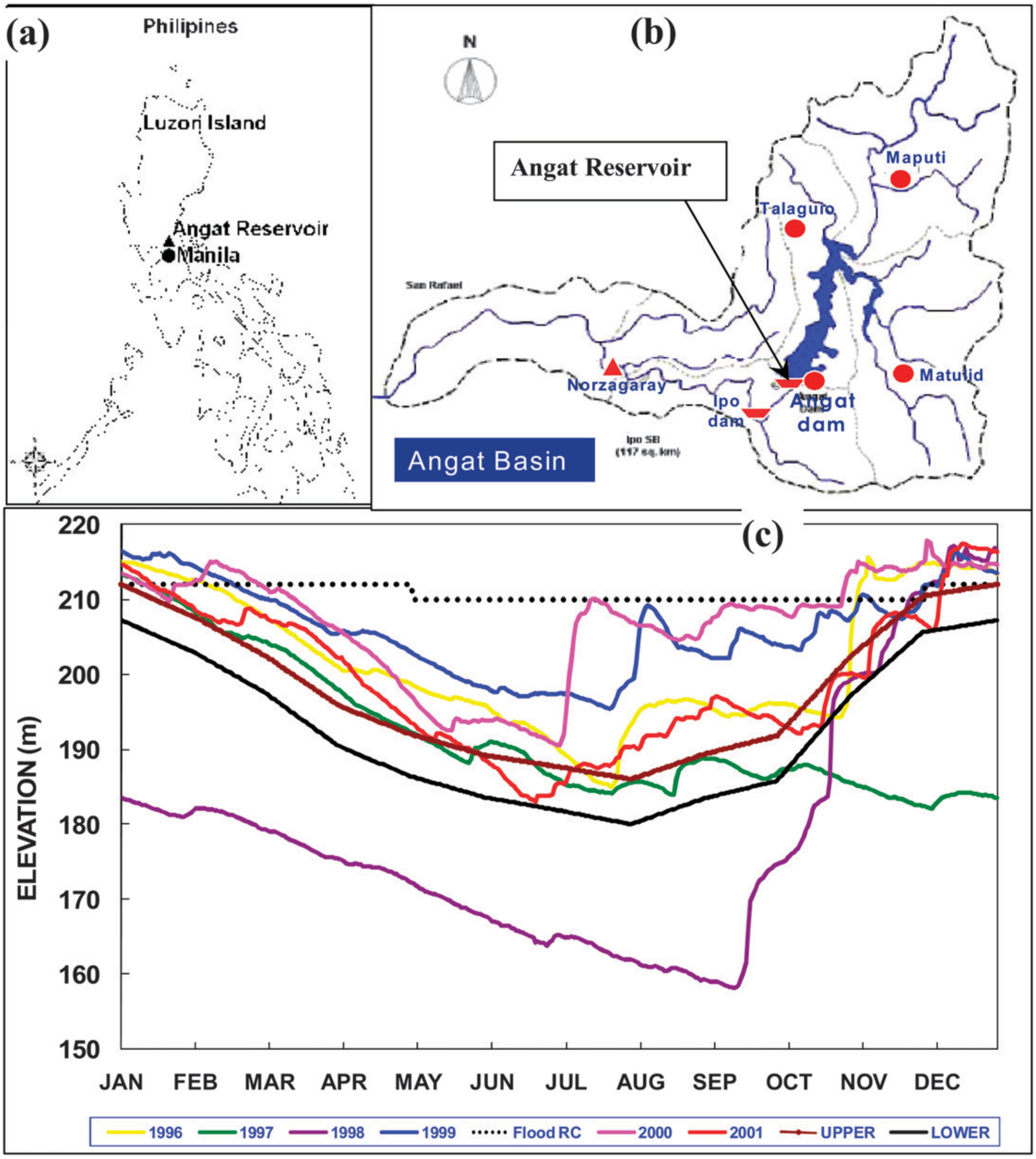

FIG. 1. (a),(b) Location of the Angat basin in the Philippines. (c) The observed reservoir storages during 1996–2001 in the Angat reservoir on Luzon Island. Panel (b) shows the Angat basin and the upstream and downstream of Angat reservoir. Panel (c) shows the currently adopted water supply rule curves (upper and lower) and flood rule curve (dotted line) along with the recorded storages during 1996–2001.

allocation for the three uses for the upcoming irrigation season in 1998. Given the low storage, authorities had decided to forego allocation for irrigation for the third consecutive season. However, with the shift to La Niña conditions in the tropical Pacific, 1998–99 ONDJF inflows were above normal. The above-normal inflows together with the foregone ONDJF irrigation season (resulting in decreased demand) resulted in excessive spillage from the reservoir.

Figures 2a and 2b show the 3-month-ahead ECHAM4.5 precipitation forecasts issued in October 1997 and in October 1998, respectively, from the International Research Institute of Climate and Society (IRI). Precipitation forecasts shown in Fig. 2 are expressed as tercile forecasts denoting the probability of below-normal (less than 33rd percentile of observed rainfall), normal (between 33rd and 67th percentile of observed rainfall), and above-normal (above 67th percentile of observed rainfall) rainfall over a given season. Figure 2b clearly shows that probability of above-normal precipitation over the Philippines is forecast to be 70%. Thus, if NWRB pursued forecast-based allocation, water for 1998 ONDJF

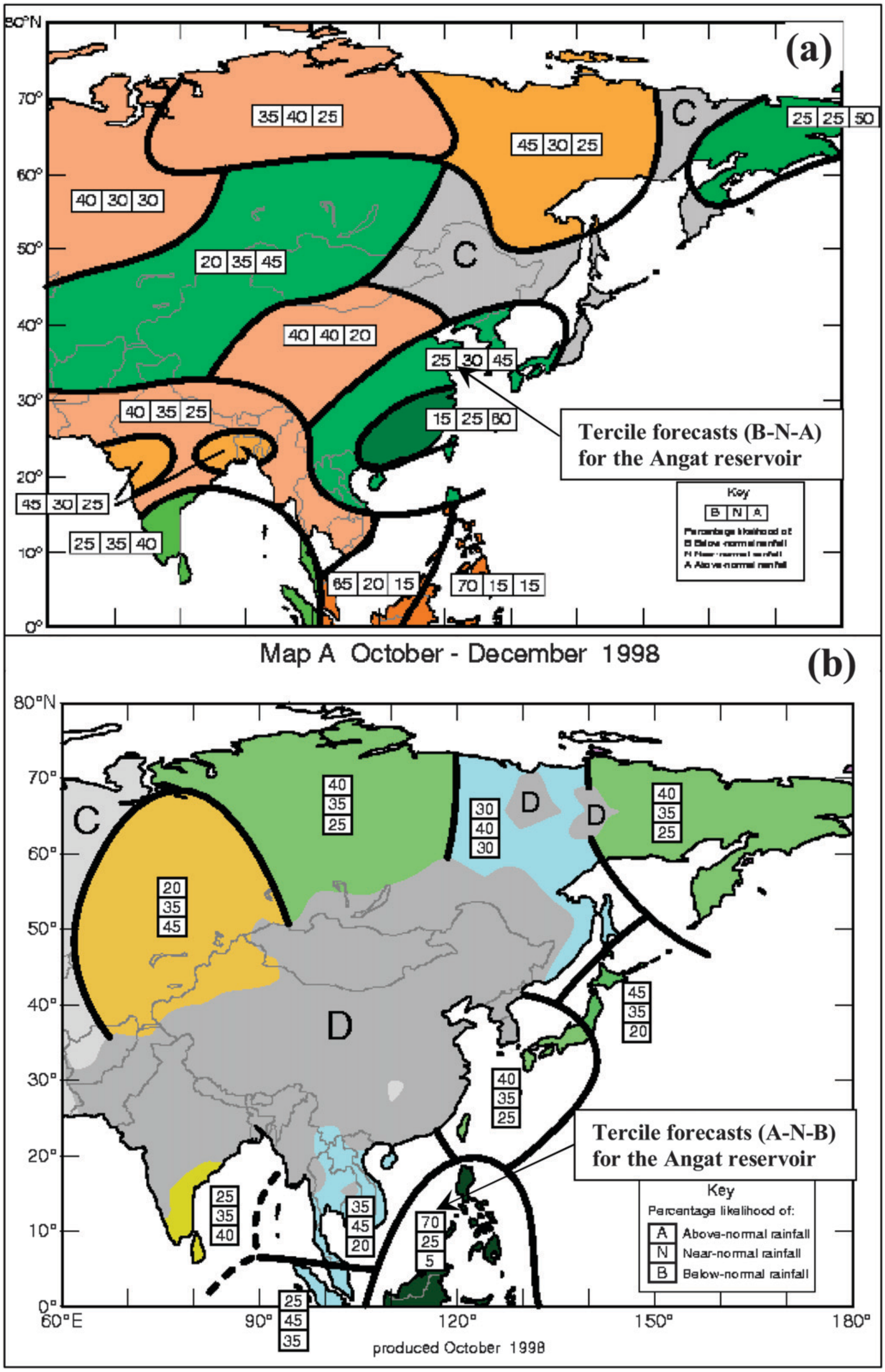

FIG. 2. Seasonal (October–December) climate forecasts issued from IRI during the 1997–98 ENSO events in (a) October 1997 and (b) October 1998. Arrows in (a) and (b) indicate the tercile forecasts relevant to the Angat reservoir. Tercile forecasts are denoted as B-N-A, with B denoting the probability of below-normal rainfall, N denoting the probability of normal rainfall, and A denoting the probability of above-normal rainfall.

irrigation could have been supplied to its fullest demand. Sankarasubramanian et al. (2008) provides detailed diagnostic analyses on strong associations between ENSO and Angat inflows during the northeast-monsoon season. In this study, we will utilize the downscaled streamflow forecasts developed by Sankarasubramanian et al. (2008) to demonstrate the utility of monthly updated climate forecasts in improving intraseasonal water allocation.

4. Probabilistic streamflow forecasts and Angat simulation model development

In this section, we briefly present details on the development of probabilistic streamflow forecasts based on the retrospective streamflow forecasts reported in Sankarasubramanian et al. (2008) and describe the Angat reservoir simulation model that takes ensembles of streamflow forecasts for allocating water for multiple uses.

a. Probabilistic reservoir inflow forecasts for the Angat basin

The probabilistic streamflow forecasts employed in this study are the ONDJF streamflow forecasts reported in Sankarasubramanian et al. (2008), which were obtained by downscaling the monthly updated precipitation forecasts from ECHAM4.5 forced with persisted SSTs. The predictors that were considered for downscaling include monthly updated precipitation forecasts from ECHAM4.5 forced with persisted SSTs, SST conditions in the tropical Pacific (Niño-3.4), and local SST conditions around the Philippines. Principal components regression (PCR) was employed to downscale the above predictors to obtain the mean monthly (conditional mean) streamflow forecasts during the ONDJF season. Thus, Sankarasubramanian et al. (2008) reported the leave-one-out cross-validated monthly streamflow forecasts, expressed as the conditional mean, and updated the forecasts each month during the ONDJF season. For additional details, see Sankarasubramanian et al. (2008).

Using the point forecast error obtained from the PCR, we obtained the conditional variance of the monthly streamflows to develop probabilistic reservoir inflow forecasts. Residual analyses of the PCR based on quantile plots and skewness tests on the residuals showed that the normality assumption is valid. By assuming that the monthly flows during the ONDJF season follow multivariate normal distribution, we developed ensembles (number of ensembles $K = 500$) of monthly streamflows using the conditional mean and the point forecast error obtained from the PCR. To ensure the month-to-month correlation between ensembles, we specify that the correlation matrix of the multivariate normal distribution is equal to the climatological month-to-month correlation between the flows. It is important to note that the covariance matrix of the multivariate normal distribution will change depending on the point forecast error of the monthly flows. As the season progresses, we update the conditional distribution of monthly streamflows based on the conditional mean and variance downscaled from the updated monthly climate forecasts. Figures 3a–e show the conditional distribution of seasonal streamflow issued each month based on the updated climate forecasts during the ONDJF season. The percentiles of the conditional distribution are obtained from the average of the ensembles of monthly streamflows. For instance, if the forecast is issued in November (Fig. 3b), then we average the monthly streamflow ensembles during November–February to obtain the reported percentiles of the conditional distribution. Figure 3f provides the ONDJF season streamflow that was obtained by averaging the best updated forecast available for each month. The best available forecast for each month during ONDJF is the forecast issued in the beginning of each month. All of the forecasts in Fig. 3 (shown for the period 1987–2001) are obtained in a leave-one-out cross-validated mode using the observed flows and the predictors available for the period 1968–2001. Table 1 provides the verification statistics of the monthly updated streamflow forecasts by summarizing the number of years during which the observed flows are less than the chosen percentile of the conditional distribution. For instance, if one is interested in the 10th percentile of the flows, which from a water management perspective corresponds to 90% reliability, then over 100 yr we can expect 10 yr to have observed flows that are less than the 10th percentile of the conditional distribution. From Table 1, we can clearly see that the monthly updated conditional distribution of streamflows preserves the marginal distribution of observed flows. We ingest these leave-one-out cross-validated probabilistic streamflow forecasts available for the period 1987–2001 to the Angat simulation model to quantify the role of updated forecasts in improving the intraseasonal water allocation during the ONDJF season.

b. Angat simulation model

The reservoir management model presented here is a simplified version of the detailed dynamic water allocation framework presented in Sankarasubramanian et al. (2003). Given that the streamflow forecasts are represented in the form of ensembles, conventional water allocation models reported in the literature [e.g., Lall and Miller 1988; for a detailed review on water allocation models, see Yeh (1985)] need to be modified

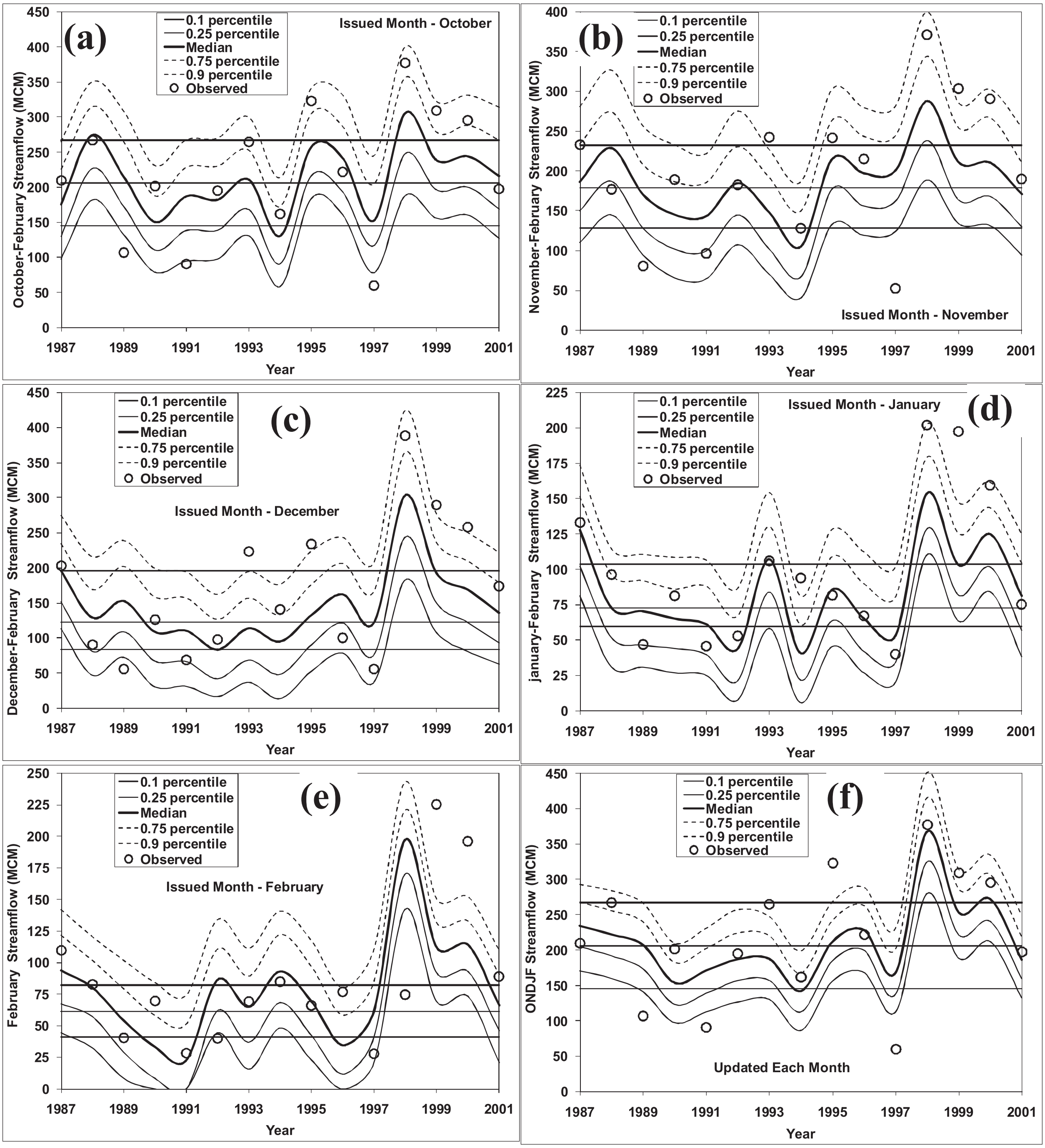

FIG. 3. Conditional distributions of updated monthly streamflow forecasts downscaled from retrospective precipitation forecasts of ECHAM4.5 forced with persisted SSTs (Sankarasubramanian et al. 2008). (a)–(e) The updated seasonal streamflow forecasts issued in the beginning of each month, October–February, for the remaining months in the ONDJF season during 1987–2001. In each panel, the forecasts are represented as the average streamflow during the rest of the months during ONDJF [e.g., (d) is the average streamflow over January and February]. (f) The combined updated forecasts for the ONDJF season.

to utilize the conditional distribution of streamflows developed contingent on the climate forecasts.

Because the current practice toward water allocation in Angat imposes priority-based allocation, with municipal having the highest priority followed by irrigation and hydropower, respectively, we intend to reflect this in the simulation model. To ensure this, the simulation model allocates water for lower-priority uses only if the

TABLE 1. Verification of the leave-one-out cross-validated probabilistic forecasts issued during the ONDJF season. Numbers in the table show the number of years (out of 34 yr: 1968–2001) during which the observed flows in a particular year are less than the predicted percentile of the issued forecast. The last row shows the number of years (out of 34 yr) during which the observed flows are expected to be lower than those of the estimated percentile from the conditional distribution.

	Percentiles = p				
Forecast-issued month	0.10	0.25	0.50	0.75	0.90
October	4	7	17	25	31
November	5	8	17	27	30
December	2	9	17	25	29
January	3	5	18	26	30
February	3	6	17	28	31
Expected	3.4	8.5	17.0	25.5	30.6

higher-priority uses' demands are fully met. In a similar way, the monthly updated streamflow forecasts are available only during the ONDJF season; we ensure with high reliability that the forecasts-based allocation would result in the end-of-February storage as suggested by the upper rule curve (shown in Fig. 1c) for supplying water during the summer (March–May).

Given the seasonal (T-month lead) ensemble inflow forecasts $q_{k,t}^{m,j}$ and initial reservoir storage $S_{t-1}^{m,j}$ at the beginning of the allocation period, where m [m = 1 (October), 2 (November), . . . , 5 (February)] denotes the forecast issue month in year j (j = 1987, 1988, . . . , 2001), k [$k = 1, 2, \ldots, K$ (=500)] represents ensembles, and t [$t = m, m + 1, \ldots, 5$ (February)] represents monthly streamflows in the ONDJF season, the Angat simulation model determines the $R_1^{m,j}, R_2^{m,j}$, and $R_3^{m,j}$ that represent the municipal, irrigation, and hydropower releases, respectively, over the ONDJF season. In addition, the water allocation model incorporates an end-of-season target storage S_T^* (T denotes the forecast lead time in months) that is associated with a failure probability p_s. For instance, in the case of Angat reservoir, S_T^* corresponds to the storage of the reservoir (S_T^*= 568.7 MCM) at 205.6 ft (1 ft $\simeq$ 30.5 cm) as per the upper rule curve in Fig. 1c. Using the basic continuity equation, we update the monthly storage equations [Eq. (1)] for each ensemble member k for the forecast issued in month m in year j:

$$S_{k,t}^{m,j} = S_{k,t-1}^{m,j} + q_{k,t}^{m,j} - E_{k,t}^{m,j} - \left(\sum_{i=1}^{3} R_{t,i}^{m,j}\right) - \mathrm{SP}_{k,t}^{m,j} \quad \text{for} \quad t = m, m+1, \ldots, 5 \quad \text{and} \quad S_{k,t-1}^{m,j} = S_{*,t-1}^{m,j} \quad \text{for} \quad t = m. \tag{1}$$

Under Eq. (1),

$$R_i^{m,j} = \sum_{t=1}^{T} R_{i,t}^{m,j}$$

denotes total release for each use i, with i = 1, 2, and 3 representing the municipal, industrial, and hydropower releases, respectively. Monthly storage equations are constrained so that the storage in each ensemble member k is between the minimum and maximum possible storage, $S_{\min}$ (=40 MCM) and $S_{\max}$ (=1011 MCM), respectively:

$$S_t = \min(S_t, S_{\max}) \quad \text{and} \quad S_t = \max(S_t, S_{\min}). \tag{2}$$

The spill $\mathrm{SP}_{k,t}^{m,j}$ occurs only if $S_{k,t}^{m,j} > S_{\max}$ and it could be obtained from Eq. (1) by specifying $S_{k,t}^{m,j} = S_{\max}$. In a similar way, all of the releases $R_{k,t}^{m,j}$ are converted into net hydropower $\mathrm{HP}_t^{m,j}$ generated from both main and auxiliary turbines based on the elevation–storage relationship of the reservoir. Evaporation $E_{k,t}^{m,j}$ is computed as a function of average storage during the month using the water surface area–storage relationship of the reservoir:

$$E_{k,t}^{m,j} = \psi_t \delta_1 [(S_{k,t}^{m,j} + S_{k,t-1}^{m,j})/2]^{\delta_2}, \tag{3}$$

where ψ_t is the monthly evaporation rate and δ_1 and δ_2 are coefficients describing the area–storage relationship. In this study, we employed spline interpolation for obtaining the water surface area corresponding to the average monthly storage computed for each ensemble. It is important to note that the evaporation is evaluated implicitly for each streamflow member in the ensemble. The average monthly lake evaporation rate ψ_t and the required monthly releases for municipal and industrial uses are given in Table 2.

The objective is to determine $R_1^{m,j}, R_2^{m,j}$, and $R_3^{m,j}$ such that the probability of having the end-of-season storage $S_T^{m,j}$ be less than the target storage S_T^* is small, which is represented by its failure probability p_s in Eq. (4):

$$\mathrm{Prob}(S_T^{m,j} < S_T^*) \le p_s. \tag{4}$$

In looking across all of the ensembles, $\mathrm{Prob}(S_T^{m,j} < S_T^*)$ is estimated by counting the number of traces in which $S_T < S_T^*$ over the total number of ensembles K from the forecast issued in month m in year j. We consider

TABLE 2. Monthly lake evaporation and the required monthly releases for municipal and irrigation uses during the ONDJF season from the Angat system. The maximum allocation for the hydropower is 2890 MCM. The total ONDJF demands for Metro Manila and for Bulacan Province irrigation are 570 and 385 MCM, respectively.

	October	November	December	January	February
Lake evaporation (mm month^{-1})	0.106	0.103	0.129	0.153	0.163
Municipal (MCM)	114	114	114	114	114
Irrigation (MCM)	154	77	77	77	0

p_s = 0.25 as indicating 75% reliability of meeting the target storage. In this study, we pursue a priority-based allocation with municipal having the highest priority followed by irrigation and hydropower use. Thus, the allocation for irrigation is considered only if the allocation for municipal use is fully met without violating the probabilistic constraint in Eq. (4). In a similar way, allocation for hydropower is considered only if the municipal and irrigation uses (in Table 2) are fully met without violating the constraint in Eq. (4).

Figure 4a shows the validation of the reservoir simulation model that compares the observed monthly storages with the modeled storages for the period 1987–2001. The modeled monthly storages are obtained by using the observed flows in Eq. (1) (instead of ensembles) to estimate the observed storages. From Fig. 4a, the developed simulation model predicts the observed monthly storages reasonably well over the period of validation. From a reservoir management perspective, ONDJF is the season in which the current practice results in increased spillage owing to the small capacity of the reservoir relative to the inflow. Figure 4b shows number of years of spilling for each month over the period 1968–2001. A total of 23 spilling events have been reported over the 34 yr of operation, with an average spill volume per event of 287 MCM, which is roughly one-half of the annual Metro Manila water allocation. It is important to note that 22 out of 23 spilling events are reported during the ONDJF season, whose inflows have been found to have significant correlation with ECHAM4.5 precipitation forecasts (Sankarasubramanian et al. 2008). We perform retrospective analyses using the above simulation model by ingesting them with monthly updated streamflow forecasts downscaled from ECHAM4.5 to estimate the releases for three uses by ensuring the end-of-season storage constraint in Eq. (4).

5. Results and analysis

In this section, we present the experimental design for evaluating the utility of monthly updated streamflow forecasts along with the results based on the retrospective reservoir analysis. We also investigate the utility of real-time precipitation forecasts issued in October from ECHAM4.5 forced with predicted SSTs to explore the possibility of improving ONDJF water allocation and for providing real-time reservoir decision support.

a. *Retrospective reservoir analysis—Experimental design*

The main intent of this study is to understand the utility of monthly updated climate forecasts in improving intraseasonal water allocation. Figure 5 shows the overall experimental design of the retrospective reservoir analyses. The proposed experimental design is analyzed under three scenarios of reservoir inflows: ONDJF allocation based on streamflow forecasts issued in the beginning of October, revisiting the October allocation based on the updated streamflow forecasts issued every month during November–February, and "climatology" (no-forecast scenario). All of the above three scenarios are utilized to estimate the releases for the three uses over the remaining months in the ONDJF season during 1987–2001 by enforcing the end-of-season storage constraint in Eq. (4). Because water demand data are not available prior to 1987, we consider reservoir analyses only for the period 1987–2001. We impose the end-of-season storage constraint in Eq. (4) because climate forecasts have poor skill beyond February (Sankarasubramanian et al. 2008).

Because the reservoir simulation model in section 4b requires an initial storage $S_{t-1}^{1,j}$ for scenario I, we consider the actual observed storage on 1 October of each year during 1987–2001. By combining the streamflow forecasts $q_{k,t}^{1,j}$ issued in October (Fig. 3a) with the observed storage in October $S_{t-1}^{1,j}$, we obtain releases for the three uses $R_1^{1,j}, R_2^{1,j}$, and $R_3^{1,j}$ by constraining Eq. (4). To evaluate the performance of the reservoir under allocation based on October forecasts, the forecasts-suggested releases $R_1^{1,j}, R_2^{1,j}$, and $R_3^{1,j}$ are combined with the observed monthly flows Q_t^j to estimate the storage in February $S_T^{1,j}$, spill $\mathrm{SP}_t^{1,j}$, and hydropower $\mathrm{HP}_t^{1,j}$. In other words, the estimates from the above simulation ($S_T^{1,j}, \mathrm{SP}_t^{1,j}$, and $\mathrm{HP}_t^{1,j}$) suggest the outcomes that would have happened in year j if one adopted the October forecast–based releases for operating the reservoir during the ONDJF season.

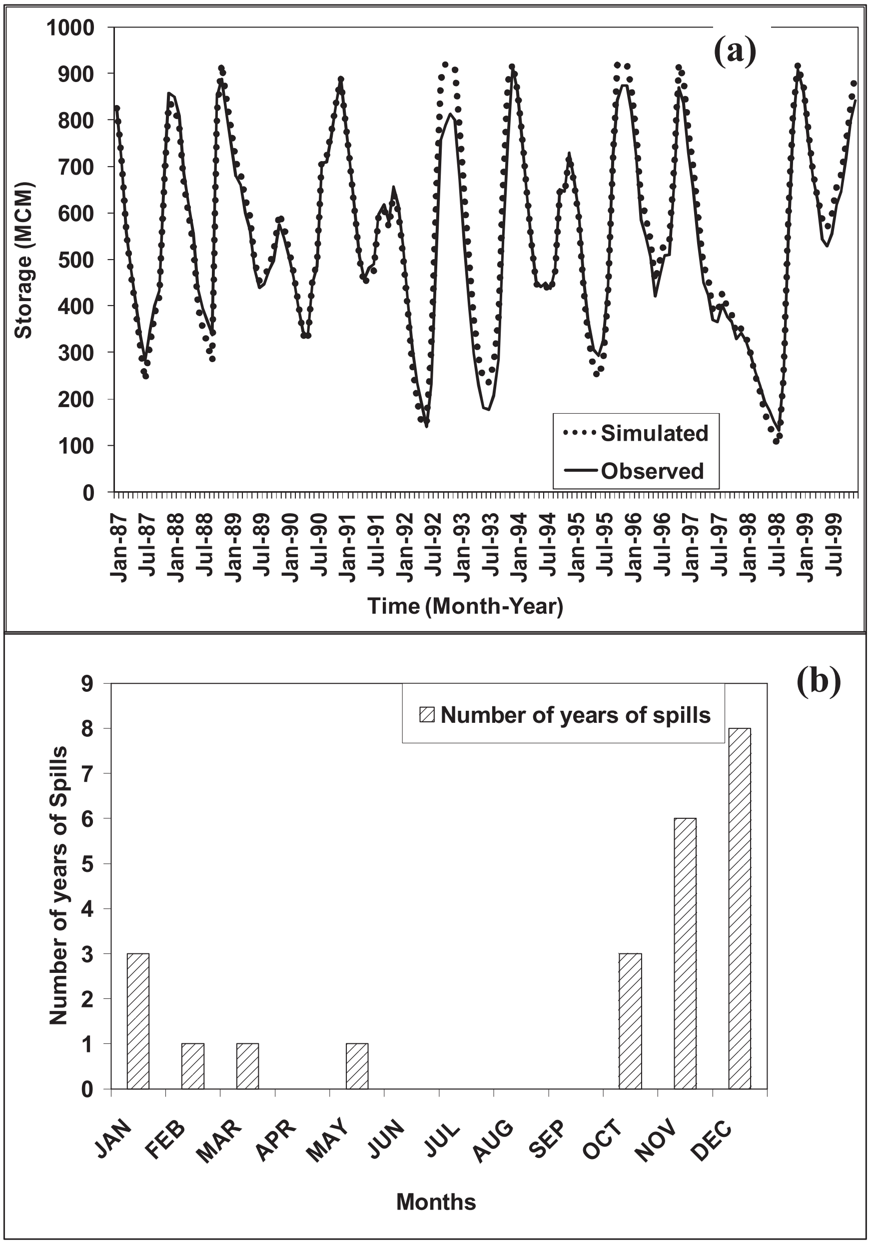

FIG. 4. (a) Validation of the Angat reservoir simulation model in predicting the monthly storages for the period 1987–2001. (b) The average number of years of spills over the period 1968–2003.

For quantifying the utility of updated streamflow forecasts issued during November–February (Figs. 3b–e) (scenario II), we consider the initial storage $S_{t-1}^{m,j}$ to be equal to the forecast-based end-of-month $(m - 1)$ storage obtained by combining $R_1^{m-1,j}$, $R_2^{m-1,j}$, and $R_3^{m-1,j}$ with observed flows Q_{m-1}^{j} in the previous month. For instance, to specify the initial storage for running the model in November in year j, we will utilize the end-of-October storage obtained by allocating the releases $R_1^{1,j}, R_2^{1,j}$, and $R_3^{1,j}$ with the observed October flows in that year. In a similar way, for specifying the beginning-of-month storage in December, we will use the end-of-November storage obtained based on November releases $R_1^{2,j}, R_2^{2,j}$, and $R_3^{2,j}$ with the observed flows in November (in year j). Thus, by combining the updated forecasts-based releases with the observed flows in that month to get the end-of-month storage for the following year, the experimental design will effectively carry out the implications of releases based on monthly updated forecasts in improving the intraseasonal water allocation.

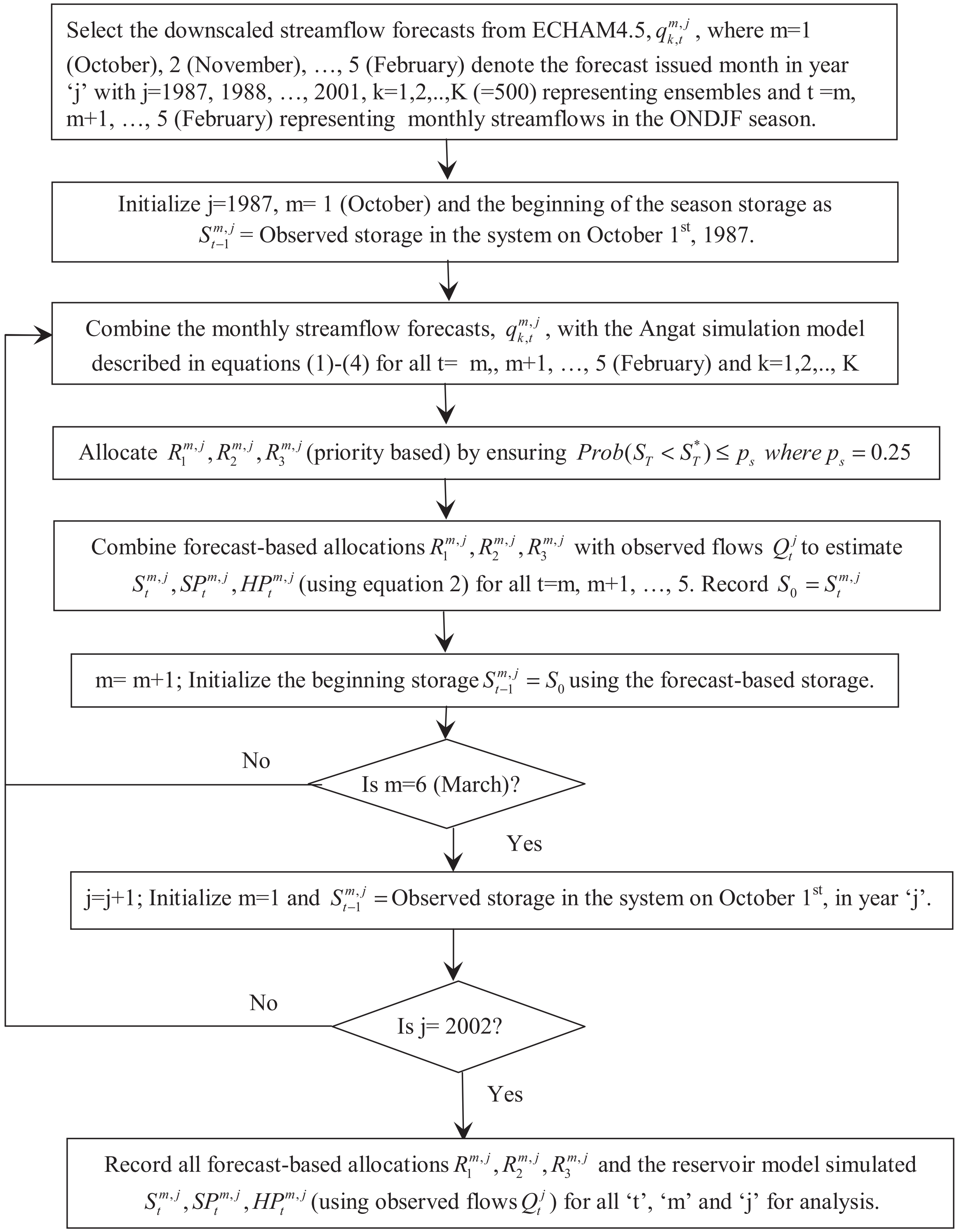

FIG. 5. Experimental design of the retrospective reservoir analyses to quantify the utility of updated climate forecasts for the Angat system.

It is important to note that the revised releases each month in a given year would result in either increased releases (usually for hydropower) or decreased releases (possibly for all of the uses) so that the probability of meeting the end-of-season storage (S_T^*) is high. Thus, if the updated forecasts suggest higher probability of above-normal inflows (in comparison with the forecast issued in the previous month), then more water could be allocated for hydropower that could potentially reduce the spill. In a similar way, if the updated forecasts suggest drier conditions, then the allocation for hydropower could be reduced to increase the probability of meeting the end-of-season target storage as well as to ensure the required releases for municipal and irrigation. Thus, for each updated forecast issued during the season, we obtain revised releases $R_1^{m,j}, R_2^{m,j}$, and $R_3^{m,j}$ and then combine the revised releases with the observed flows Q_t^j during the season to estimate the storages $S_t^{m,j}$, spill $\mathrm{SP}_t^{m,j}$, and hydropower $\mathrm{HP}_t^{m,j}$ for each month during the season. The study will use the above simulated estimates of spill, storages, and hydropower to quantify the utility of updated streamflow forecasts.

We will also compare the reservoir performance, in terms of reduced spills and increased releases and hydropower generated, from scenarios I and II with the performance of the reservoir under climatological (no forecast) information (scenario III). To develop climatological ensembles, we simply bootstrap the observed seasonal streamflows during 1968–2001, since there is no year to year correlation in ONDJF streamflows. The observed monthly flows from the bootstrapped seasonal flow will basically provide the monthly climatological streamflow ensembles. The simulated storages and spill estimates obtained using climatological ensembles are compared with the reservoir performance under October forecasts and monthly updated forecasts. The next four sections discuss results from retrospective reservoir analysis.

b. *Allocation under streamflow forecasts issued in October (scenario I)*

Figure 6 compares the water allocation ($R_2^{1,j}, R_2^{1,j}$, and $R_3^{1,j}$) obtained using the ONDJF monthly streamflow forecasts (in Fig. 3a) with the water allocated (Fig. 6b) using climatological forecasts for the period 1987–2001. For this purpose, both analyses started with the observed storage in the reservoir on 1 October as the initial storage $S_{t-1}^{1,j}$. Figure 6 also shows the observed monthly average flows, indicating the tercile category (≤33rd percentile of observed flows is below normal; >67th percentile of observed flows is above normal; otherwise normal) under which they fell.

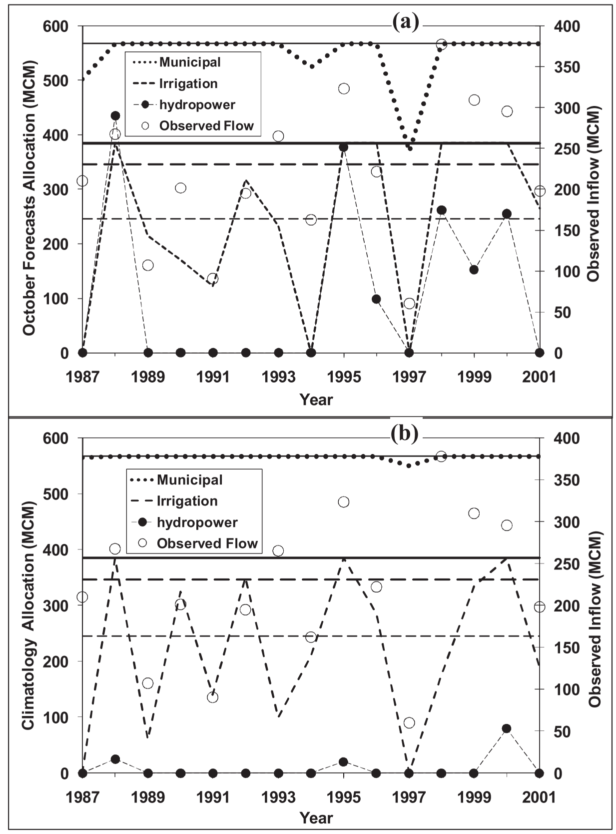

FIG. 6. (a) Comparison of water allocation ($R_1^{1,j}$, $R_2^{1,j}$, and $R_3^{1,j}$) using the monthly streamflow forecasts issued in October (Fig. 3a) with the (b) allocation obtained using climatological ensembles for the ONDJF season for the three uses—municipal, irrigation, and hydropower—during 1987–2001. Solid horizontal lines at 567.5 MCM (thin) and at 385 MCM (thick) denote the municipal (Metro Manila) and irrigation demand, respectively. Dashed horizontal lines at 164 MCM (thin line) and at 231 MCM (thick line), respectively, denote the 33rd and 67th percentiles of observed flow during the ONDJF season.

We first focus our discussion on the 1997–98 ENSO episodes. The allocation in 1997, given that the forecasts suggest below-normal year, is only 370 MCM (instead of the required 567.5 MCM) and no water is allocated for irrigation and hydropower. On the other hand, climatology suggests 550 MCM for municipal. It is important to note that the water that could be allocated during a season does not depend only on the streamflow potential, but also on the initial storage. In section 3, we discussed the missed opportunity of not utilizing forecasts to suggest irrigation in the 1998 ONDJF season (primarily due to low initial storage in October). Based on Fig. 6a, we clearly see that the forecasts-based allocation suggests release of required demands for municipal and irrigation uses along with an additional allocation of 262 MCM for hydropower. In comparison to this, the climatological ensembles suggest an allocation of 175 MCM for irrigation with no additional water for hydropower. Because the analysis considers priority-based water allocation, all of the demand for municipal was first met before allocating irrigation. Thus, utilizing the climate forecasts for ONDJF water allocation in 1997–98 would have resulted in preparing additional contingency measures to meet municipal demand for the 1997 season and allocation for irrigation in the 1998 season.

Looking at all of the above-normal years (1988, 1995, 1998, 1999, and 2000), it is clear that the 5-months-lead streamflow forecasts suggest availability of additional water for hydropower beyond the required demands for municipal and irrigation uses. In contrast, the climatological ensembles suggest lesser/no allocation for irrigation and hydropower uses during above-normal years. On the other hand, during below-normal years (1991, 1994, and 1997), forecasts suggest less water for irrigation in comparison with the amount allocated by climatology with no water being allocated for hydropower. Only for 1989 do forecasts suggest more water for irrigation, indicating a missed opportunity for identifying a dry year. This is because the streamflow forecasts shown in Fig. 3a suggest an above-normal year (tercile forecasts are 0.23, 0.29, and 0.41 for below-normal, normal, and above-normal categories, respectively), indicating more water available for allocation. However, by updating the forecasts every month through the ONDJF season, we show that allocations for the three uses could be revised based on the updated streamflow potential. The next section discusses the utility of updated forecasts in revising the allocations suggested by the October forecasts.

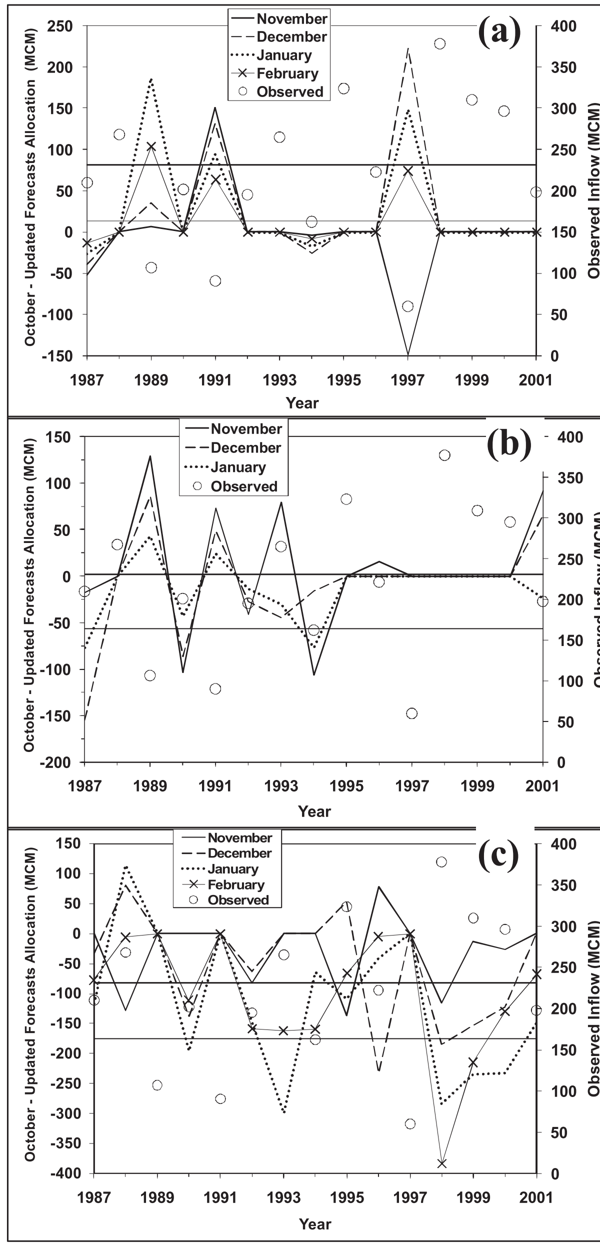

FIG. 7. (a)–(c) Utility of monthly updated streamflow forecasts in improving water allocation, showing the difference in allocation (shown in Fig. 6a) obtained using the forecasts available in October and the allocation obtained using the updated forecasts available during November–February for Metro Manila, irrigation, and hydropower, respectively. Solid horizontal lines at 164 MCM (thin line) and at 231 MCM (thick line), respectively, denote the 33rd and 67th percentiles of observed flows during the ONDJF season.

c. Reservoir performance under monthly updated streamflow forecasts (scenario II)

Given that the main intent of the research is to quantify the utility of monthly updated climate forecasts in improving intraseasonal water allocation, we combine the updated streamflow forecasts (Figs. 3b–e) with the initial storage $S_{t-1}^{m,j}$ that would have resulted if one had applied previous-month-forecast-suggested releases. In other words, we obtain $S_{t-1}^{m,j}$ by combining $R_1^{m-1,j}$, $R_2^{m-1,j}$, and $R_3^{m-1,j}$ with the observed flows Q_{t-1}^{j} in the previous month. We repeat this procedure every month to estimate releases, storages, spill, and generated hydropower that would have resulted if one updated the releases every month so that the probability of meeting the end-of-season storage is always 0.75.

Figures 7a–c show the difference between the releases that are due for the remaining months in the season based on the October forecasts and the allocation obtained for the rest of the season utilizing the monthly updated streamflow forecasts for the three uses. Thus, to compare the performance of October forecasts with updated forecasts, it is important to consider the releases that are due for the rest of the season based on the October allocation. For instance, if the difference is zero for a given use, then it implies that the updated forecasts suggest allocating the same quantity as promised by the October forecasts. On the other hand, if the difference is positive (negative), then the updated forecasts suggest drier (wetter) conditions than the streamflow potential suggested by the October forecasts. Thus, if the updated forecasts suggest drier conditions, we ensure the priority-based water allocation, with hydropower receiving reduced allocation followed by reduced allocation for irrigation and municipal use. In a similar way, if the updated forecasts suggest wetter conditions, then we increase the allocation for Metro Manila first (until the entire demand for the rest of the season is met) followed by an increase in allocation for irrigation and hydropower uses.

From Fig. 7a, we see clearly that updated forecasts during the season (November–February) suggest reduced allocation for Metro Manila during below-normal years (1989, 1991, and 1997) to ensure the end-of-season target storage is met. In a similar way, in those years, reduced allocations for irrigation (Fig. 7b) are suggested with hydropower (Fig. 7c) receiving no additional allocation based on the updated streamflow forecasts. The difference in hydropower allocation is zero since the October forecast itself did not allocate any water (Fig. 6a) during below-normal years. Figure 7a also shows increased allocation (implying more water available) for municipal use in 1997 based on forecasts issued in November, which is a missed opportunity in predicting below-normal condition. This could be understood by comparing the streamflow forecasts issued in October (shown as percentiles) (Fig. 3a) and the updated forecasts issued in November (Fig. 3b), which suggests an upward shift in the percentiles in comparison with the climatological percentiles. However, we show in section 5d that the reduced allocation using updated forecasts during December–February suggests reduced allocation resulting in meeting the end-of-season target storage in February.

Under normal years (1987, 1990, 1992, 1994, 1996, 2001), updated forecasts suggest allocation of entire demand for municipal use. For irrigation, the updated forecasts suggest increased water availability in comparison with the allocations suggested by the October forecasts. For instance, in 1987 and 1994, October forecasts suggest no allocation (Fig. 6a) for irrigation. However, updated forecasts (Fig. 7b) issued during the season allocate additional water for irrigation. This suggests the potential utility of updated climate forecasts in delaying the commencement of the irrigation season.

During above-normal years (1988, 1993, 1995, 1998–2000), it is very clear that the updated forecasts suggest additional allocations for all of the uses. From Fig. 7a, we understand that updated forecasts suggest that the total demand for Metro Manila could be met throughout the season. For irrigation, updated forecasts suggest availability of enough water to meet the total seasonal demand during above-normal years. Only the updated forecasts issued in November 1993 suggest reduced allocation for irrigation (Fig. 7b) in comparison with the allocation suggested by the October forecasts. However, the main utility of updated forecasts in above-normal years is in suggesting increased water allocation for hydropower based on the updated streamflow potential. For instance, in 1998, because the updated forecasts suggest increased streamflow potential (Figs. 3b–e) in comparison with the October forecasts (Fig. 3a), additional water is allocated for hydropower, which could potentially reduce spillage and increase the generated hydropower. We can also see that the updated forecasts suggest additional water for hydropower within the season during 1999–2000. However, it is important to evaluate the performance of the reservoir under these forecasts-based allocations. The next two sections perform that analysis by combining the forecasts-based allocation with the observed ONDJF flows during 1987–2001 to quantify the improvements in intraseasonal water allocation.

d. Meeting the end-of-season target storage

Given that the skill in predicting the streamflow is present only during the ONDJF season (Sankarasubramanian et al. 2008), we intend to apply the downscaled streamflow forecasts in such a way that the forecasts-based allocation would not result in February storage being lower than the target storage specified by the upper rule curve ($S_T^* = 568.7$ MCM). Thus, the allocation for each month, $R_1^{m,j}$, $R_2^{m,j}$, and $R_3^{m,j}$, is constrained based on Eq. (4) to ensure enough water in the reservoir to meet the Metro Manila demand during the summer.

Figure 8 shows the simulated February storages $S_T^{m,j}$ by combining the monthly updated releases $R_1^{m,j}$, $R_2^{m,j}$, and $R_3^{m,j}$ with the observed flows Q_t^j during three below-normal years (1989, 1991, and 1997) . During normal and above-normal years (i.e., years others than 1989, 1991, and 1997), forecasts-based allocation resulted with the end-of-February storage being greater than S_T^* upon simulation with the observed flows. From Fig. 8, we can infer that the simulated end-of-season storage $S_T^{1,j}$ based on the forecasts issued in October is smaller than the target storage S_T^*. However, as we continuously revise the allocation by enforcing Eq. (4) based on the monthly updated forecasts, the simulated end-of-season storage $S_T^{m,j}$ increases. We can infer this from Figs. 7a-7c as allocation based on the updated forecasts is reduced in

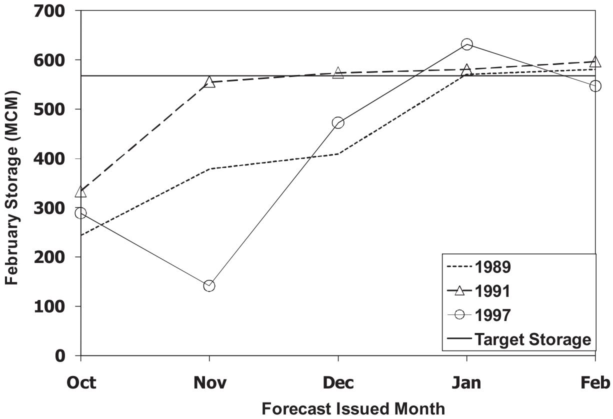

FIG. 8. Ability of monthly updated streamflow forecasts (shown in Figs. 3a–e) in meeting the end of season storage in February $S_T^{m,j}$ obtained based on the allocation $R_1^{m,j}$, $R_2^{m,j}$, and $R_3^{m,j}$ shown in Figs. 6a and 7a–c. The end-of-season storages are obtained by simulation with observed flows based on the allocation suggested by the monthly updated forecasts for the three uses.

comparison with the allocation (Fig. 6a) suggested by the October forecasts. Thus, only allocation based on the January forecasts ensures that the simulated February storage $S_T^{4,j}$ is greater than S_T^*. This indicates that revising the allocation based on the updated streamflow potential results in improved intraseasonal water allocation by ensuring enough water to meet the summer demand through restrictions/rationing among the three uses.

e. Maximizing hydropower generation contingent on monthly updated forecasts

Given that hydropower generation has the lowest priority among the three uses, we intend to show how the monthly updated climate forecasts could be utilized for generating additional hydropower. For this purpose, we simulate the reservoir performance during 1987–2001 using the forecast-suggested releases $R_1^{m,j}$, $R_2^{m,j}$, and $R_3^{m,j}$ shown in Figs. 6a and 7a–c with the observed flows Q_t^j to obtain storages, spill, and hydropower ($S_t^{m,j}$, $\mathrm{SP}_t^{m,j}$, and $\mathrm{HP}_t^{m,j}$) based on each month's forecasts over the ONDJF season. Figures 9a and 9b show the generated hydropower and the spill that would have occurred during the ONDJF season if one adopted the monthly updated forecasts-based releases or the climatological ensembles. Thus, the hydropower and spill under the "updated" category are obtained by summing up the total hydropower

$$\mathrm{HP}^{\mathrm{updated},j} = \sum_{\substack{m=1\\t=m}}^{5} \mathrm{HP}_t^{m,j}$$

and spill

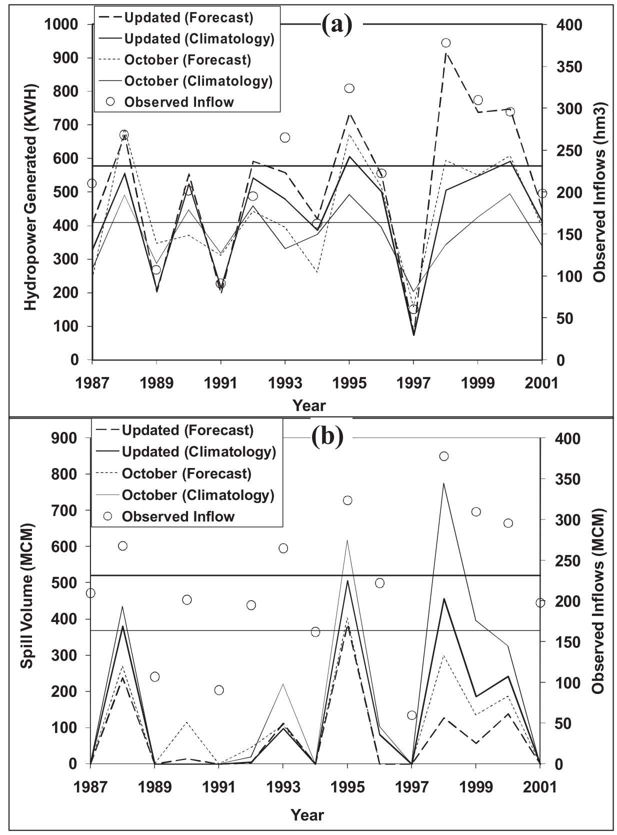

FIG. 9. Utility of updated streamflow forecasts in (a) improving hydropower generation $\mathrm{HP}^{m,j}$ and in (b) reducing the reservoir spill $\mathrm{SP}^{m,j}$ during the ONDJF season. Both the hydropower generated and the reservoir spill are obtained by simulating the allocation (Fig. 6a) obtained using October forecasts (Fig. 3a) and the allocation (Figs. 7a–c) obtained using updated forecasts (Figs. 3b–e) with the observed flows. Solid horizontal lines at 164 MCM (thin line) and at 231 MCM (thick line), respectively, denote the 33rd and 67th percentiles of observed monthly average flow during the ONDJF season.

$$\mathrm{SP}^{\mathrm{updated},j} = \sum_{\substack{m=1\\t=m}}^{5} \mathrm{SP}_t^{m,j}$$

over the ONDJF season utilizing the monthly updated forecasts (Figs. 6a, 7a–c) or climatological ensembles. Under the category for "October," we report the total hydropower

$$\mathrm{HP}^{1,j} = \sum_{t=1}^{5} \mathrm{HP}_t^{1,j}$$

and spill

$$\mathrm{SP}^{1,j} = \sum_{t=1}^{5} \mathrm{SP}_t^{1,j}$$

obtained during the ONDJF season based on the allocation suggested by October forecasts (Fig. 6a) or climatology (Fig. 6b, see Fig. 5 for additional details).

From Fig. 9a, we can clearly see that during above-normal and normal years the hydropower generated from monthly updated forecasts is higher than the hydropower generated based on climatological ensembles utilizing the October forecasts. The hydropower generated from the October forecasts represents the total hydropower generated during the ONDJF season if one had just pursued the releases shown in Fig. 6a. Figure 9b shows precisely that the increased hydropower generation is obtained primarily by reduction in spillage from the reservoir. From Fig. 9a, we can see that for 1998 the hydropower generated based on the October forecasts as well as based on the updated forecasts (Fig. 9a) is higher in comparison with the hydropower generated by climatology, which is primarily due to reduced spillage. On the other hand, during below-normal years, we can see that the hydropower generated from the updated forecasts is less than the hydropower generated using the October forecasts, since the updated forecasts suggest reduced allocation for hydropower (Fig. 7c). We can also see that no spillage (Fig. 9b) is reported during below-normal years under forecasts/climatology.

It is also interesting to note that during certain years (1987, 1990, 1992, 1993, 1994, and 2001), monthly updated climatological ensembles generate more hydropower during the ONDJF season than the hydropower generated by the forecasts issued in October. Though the climatological ensembles do not have any skill, as part of the experimental design (Fig. 5) we update the storage at the end of the month by combining the releases suggested by the climatological ensembles with the previous month's observed flow. This updated storage results in increased initial storage for the next month, resulting in more water available for hydropower allocation. This implies that monitoring the reservoir conditions (based on the updated storage) to develop a revised allocation policy (without forecasts) within the season could result in better benefits than pursuing allocation based on the forecasts available in the beginning of the season.

f. Reservoir performance utilizing real-time climate forecasts from ECHAM4.5

Because statistical downscaling requires climate forecasts issued for prior years, we employed retrospective monthly precipitation forecasts from the ECHAM4.5 GCM forced with globally persisted SSTs for developing Angat streamflow forecasts in section 4. The simplest approach to forecast the SSTs is through persisting SSTs over the forecasting period of interest. For instance, if the December 2005 SST at a particular grid point is 1.5°C above its climatological value, then an anomalous 1.5°C is persisted for 5 months above the respective month's climatology at that grid point to develop the boundary conditions for forcing the GCMs. However, real-time precipitation forecasts are obtained by forcing the GCMs with predicted SSTs for the tropical oceans from three SST prediction models [National Centers for Environmental Prediction (NCEP) model, Lamont-Doherty ocean–atmosphere model, and constructed analog model] and by persisting the anomalous SSTs over the forecasting period. (At the time of writing, additional information on the two-tier forecasting scheme at IRI was available online in the tutorial at http://iri.columbia.edu/climate/forecast/tutorial2/.)

In this section, we employ the PCR equations developed earlier using the retrospective precipitation forecasts from ECHAM4.5 forced with persisted SSTs (section 4a) to develop streamflow forecasts based on the real-time ONDJF precipitation forecasts from ECHAM4.5 forced with predicted SSTs for the period 1996–2005. The downscaled 5-months-ahead streamflow forecasts (available in October) are then ingested into the Angat simulation model to estimate the releases $R_1^{1,j}$, $R_2^{1,j}$, and $R_3^{1,j}$ for each use. We do not consider any updated forecasts under this category, since the monthly updated real-time climate forecasts are available only from 2002. For additional details on the development of streamflow forecasts for the Angat reservoir using real-time precipitation forecasts from ECHAM4.5 forced with predicted SSTs, see Sankarasubramanian et al. (2008).

Figure 10 compares the allocation ($R_1^{1,j}$, $R_2^{1,j}$, and $R_3^{1,j}$) based on the streamflow forecasts developed using real-time precipitation forecasts from ECHAM4.5 forced with predicted SSTs with the allocation based on the climatological ensembles. From Fig. 10a, we clearly see that during above-normal years the forecasts-based allocation suggests additional water for hydropower in comparison with the allocation based on climatology. From comparing Figs. 10a and 6a for the period 1996–2001, we infer that the streamflow forecasts developed using real-time precipitation forecasts suggest lower water availability for the same $p_s = 0.25$. For instance, in Fig. 10a, the amount of water allocated for hydropower in 1998 is 15 MCM, which is less than the amount of water allocated for hydropower (262 MCM in Fig. 6a) using the retrospective precipitation forecasts from ECHAM4.5. However, in comparison with climatology, streamflow forecasts developed using real-time precipitation forecasts perform better in reducing/increasing additional water according to the change in streamflow potential.

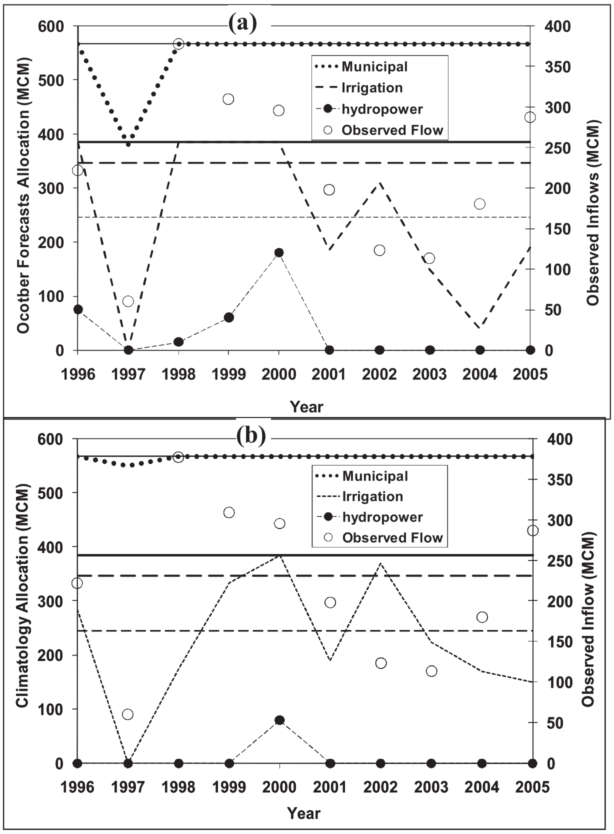

FIG. 10. Performance of downscaled streamflow forecasts obtained (a) using real-time precipitation forecasts from ECHAM4.5 forced with predicted SSTs (issued in October) in setting up allocation ($R_1^{1,j}$, $R_2^{1,j}$, and $R_3^{1,j}$) and (b) using climatology for the ONDJF season. Dashed horizontal lines at 164 MCM (thin line) and at 231 MCM (thick line), respectively, denote the 33rd and 67th percentiles of observed flows during the ONDJF season.

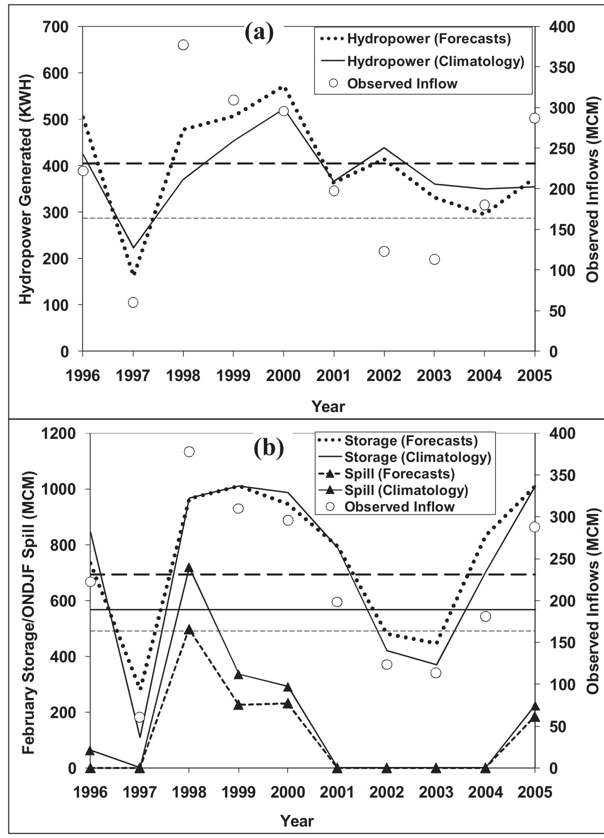

FIG. 11. Performance of the reservoir (a) in generating hydropower by reducing the spillage [lines with triangle marker shown in (b)] and in (b) meeting the end-of-season storage utilizing the real-time precipitation forecasts issued in October from ECHAM4.5 forced with predicted SSTs. The solid horizontal lines at 568.7 MCM show the end-of-season target storage. Dashed horizontal lines at 164 MCM (thin line) and at 231 MCM (thick line), respectively, denote the 33rd and 67th percentiles of observed flows during the ONDJF season.

Figure 11 combines the releases $R_1^{1,j}$, $R_2^{1,j}$, and $R_3^{1,j}$ in Fig. 10 with the observed inflows Q_t^j to simulate the storages, spill, and hydropower ($S_t^{1,j}$, $\mathrm{SP}_t^{1,j}$, and $\mathrm{HP}_t^{1,j}$) for the period 1996–2005. From Fig. 11a, we infer that the hydropower generated,

$$\mathrm{HP}^{1,j} = \sum_{t=1}^{5} \mathrm{HP}_t^{1,j},$$

using the real-time precipitation forecasts is higher (lower) during above-normal (below normal) years in comparison with the hydropower generated using climatological ensembles. In a similar way, Fig. 11b shows the simulated storage at the end of February ($S_T^{1,j}$) and spill,

$$\mathrm{SP}^{1,j} = \sum_{t=1}^{5} \mathrm{SP}_t^{1,j},$$

based on the downscaled streamflow forecasts and climatology. We can see from Fig. 11b that the increased hydropower generated from the forecasts during above-normal years primarily arises from the reduction in spillage. During below-normal years, the reduced hydropower generated from forecasts (Fig. 11a) primarily results from reduced allocation for irrigation (Fig. 10a). Further, from Fig. 11b, we see that the simulated February storage is lower than the February target storage ($S_T^* = 568.7$ MCM) in three below-normal years (1997, 2002, and 2003). However, based on the updated forecast analysis shown in section 5c, we could expect that the allocation for municipal and irrigation needs to be decreased during the season to ensure enough water in the reservoir to meet the summer demand.

The main intent of the analysis in this section is to show that the PCR equations obtained using retrospective climate forecasts could be effectively utilized for downscaling real-time precipitation forecasts to support seasonal water allocation from the Angat reservoir. As the length of real-time precipitation forecasts increases, a new set of PCR equations could be developed using the real-time precipitation forecast itself for forecasting seasonal inflows into the Angat reservoir. Similarly, as the length of monthly updated real-time climate forecasts increases, we could utilize them to downscale the streamflow forecasts within the season for improving intraseasonal water allocation. However, the presented analyses clearly show that the downscaled streamflow forecasts using real-time precipitation forecasts perform better than the climatology and result in improved seasonal water allocation for the ONDJF season.

6. Summary and conclusions

Monthly updated reservoir inflow forecasts developed by Sankarasubramanian et al. (2008) were employed in the study to improve the intraseasonal water allocation during October–February (ONDJF) for the Angat reservoir, a multipurpose system, in the Philippines. The inflow forecasts downscaled from retrospective climate forecasts from ECHAM4.5 forced with persisted SSTs were represented probabilistically using the conditional mean and the point forecast error obtained from the downscaled PCR equations. Monthly updated probabilistic inflow forecasts during the ONDJF season were ingested into the Angat simulation model to estimate the releases for three uses—Metro Manila, Bulacan irrigation, and hydropower—in such a way that the probability of meeting the end-of-season target storage ($S_T^* = 568.7$ MCM) was high ($1 - p_s = 0.75$). The forecasts-based allocations were compared with the climatology allocation for the period 1987–2001 by combining the allocations with the observed flows to quantify the spill, storages, and hydropower generated from the system. The performance of the reservoir was also evaluated using the reservoir inflow forecasts downscaled from real-time precipitation forecasts from ECHAM4.5 forced with predicted SSTs.

Retrospective reservoir analyses clearly show that the 5-months-ahead forecasts could be effectively utilized for quantifying the releases during the ONDJF season. The allocation suggested by the forecasts varies according to the inflow potential resulting in more (less) water for hydropower during above-normal (below normal) years. Further, based on the updated forecasts issued every month in the ONDJF season, October allocation could be revised by ensuring additional (less) water for the three uses if the updated forecasts suggest wet (dry) conditions. Combining the releases with the observed inflows during the ONDJF season shows that the monthly updated forecasts improve intraseasonal water allocation by reducing the spill and increasing the hydropower generation during above-normal years. In a similar way, during below-normal years, the updated forecasts reduce allocation for hydropower by ensuring that the municipal and irrigation demands are met first with a high probability (75%) of meeting the end-of-season target storage. The retrospective reservoir analysis also confirmed that out of 15 yr the end-of-season target storage was met in 12 yr using the October forecasts alone. However, by updating the forecasts continually throughout the season, the reduced allocation for municipal and industrial uses ensured that the February storage could be met in all of the years except 1997. Thus, the analyses show that by pursuing forecasts-based allocation the risk of not having enough water for the summer season (March–June) could be effectively reduced. Further, the study also shows that streamflow forecasts issued in October from real-time precipitation forecasts from ECHAM4.5 forced with predicted SSTs perform better in allocating water for the three uses in comparison with the climatology-based allocation.

Given that climate forecasts are issued/updated continually on a monthly basis, it is important that water managers utilize them to develop probabilistic forecasts of storage conditions in the reservoir conditional on the forecasts-based releases. Such experimental/real-time reservoir analyses using real-time precipitation forecasts will offer additional insights on the difficulties and challenges in utilizing climate information for improving water management. Further, because real-time climate forecasts are nowadays obtained by combining multiple GCMs, it would be prudent to utilize streamflow forecasts downscaled from multimodel climate forecasts. Recent studies have shown that multimodel streamflow forecasts developed from two low-dimensional statistical models (Devineni et al. 2008) provide reduced false alarms and missed targets in predicting storage conditions and in developing release scenarios for the Falls Lake reservoir in North Carolina (Golembesky et al. 2009). Our future studies will focus on downscaling multimodel climate forecasts to develop inflow forecasts for the Angat system and to use them for performing experimental reservoir analysis to improve both seasonal and intraseasonal water allocation in the Angat basin.

Acknowledgments. We thank the three anonymous reviewers whose valuable comments led to significant improvements in our manuscript. We also thank the National Water Resources Board of the Philippines for providing the data for modeling and analyses.

REFERENCES

Carpenter, T. M., and K. P. Georgakakos, 2001: Assessment of Folsom Lake response to historical and potential future climate scenarios: 1. Forecasting. *J. Hydrol.,* **249** (1–4), 148–175.

de Souza Filho, F. A., and U. Lall, 2003: Seasonal to interannual ensemble streamflow forecasts for Ceara, Brazil: Applications of a multivariate, semiparametric algorithm. *Water Resour. Res.,* **39,** 1307, doi:10.1029/2002WR001373.

Dettinger, M. D., and H. F. Diaz, 2000: Global characteristics of stream flow seasonality and variability. *J. Hydrometeor.,* **1,** 289–310.

Devineni, N., A. Sankarasubramanian, and S. Ghosh, 2008: Multimodel ensembles of streamflow forecasts: Role of predictor state space in skill evaluation. *Water Resour. Res.,* **44,** W09404, doi:10.1029/2006WR005855.

Gangopadhyay, S., M. Clark, and B. Rajagopalan, 2005: Statistical downscaling using *K*-nearest neighbors. *Water Resour. Res.,* **41,** W02024, doi:10.1029/2004WR003444.

Georgakakos, A. P., H. M. Yao, M. G. Mullusky, and K. P. Georgakakos, 1998: Impacts of climate variability on the operational forecast and management of the upper Des Moines River basin. *Water Resour. Res.,* **34,** 799–821.

Georgakakos, K. P., and N. E. Graham, 2008: Potential benefits of seasonal inflow prediction uncertainty for reservoir release decisions. *J. Appl. Meteor. Climatol.,* **47,** 1297–1321.

Golembesky, K., A. Sankarasubramanian, and N. Devineni, 2009: Improved drought management of Falls Lake Reservoir: Role of multimodel streamflow forecasts in setting up restrictions. *J. Water Resour. Plann. Manage.,* **135,** 188–197.

Guetter, A. K., and K. P. Georgakakos, 1996: Are the El Niño and La Niña predictors of the Iowa River seasonal flow? *J. Appl. Meteor.,* **35,** 690–705.

Hamlet, A. F., and D. P. Lettenmaier, 1999: Columbia River streamflow forecasting based on ENSO and PDO climate signals. *J. Water Resour. Plann. Manage.,* **125,** 333–341.

——, D. Huppert, and D. P. Lettenmaier, 2002: Economic value of long-lead streamflow forecasts for Columbia River hydropower. *J. Water Resour. Plann. Manage.,* **128,** 91–101.

Hartmann, H. C., T. C. Pagano, S. Sorooshian, and R. Bales, 2002: Confidence builders: Evaluating seasonal climate forecasts from user perspectives. *Bull. Amer. Meteor. Soc.,* **83,** 683–698.

Kyriakidis, P. C., N. L. Miller, and J. Kim, 2001: Uncertainty propagation of regional climate model precipitation forecasts to hydrologic impact assessment. *J. Hydrometeor.,* **2,** 140–160.

Lall, U., and C. W. Miller, 1988: An optimization model for screening multipurpose reservoir systems. *Water Resour. Res.,* **24,** 953–968.

Lettenmaier, D. P., and E. Wood, 1993: Hydrologic forecasting. *Handbook of Hydrology,* V. Maidment, Ed., McGraw-Hill, 26.1–26.30.

Leung, L. R., A. F. Hamlet, D. P. Lettenmaier, and A. Kumar, 1999: Simulations of the ENSO hydroclimate signals in the Pacific Northwest Columbia River basin. *Bull. Amer. Meteor. Soc.,* **80,** 2313–2329.

Maurer, E. P., and D. P. Lettenmaier, 2004: Potential effects of long-lead hydrologic predictability on Missouri River mainstem reservoirs. *J. Climate,* **17,** 174–186.

National Research Council, 2002: *Report of a Workshop on Predictability & Limits-To-Prediction in Hydrologic Systems.* National Academies Press, 138 pp.

Pagano, T. C., H. C. Hartmann, and S. Sorooshian, 2001: Using climate forecasts for water management: Arizona and the 1997–1998 El Niño. *J. Amer. Water Resour. Assoc.,* **37,** 1139–1153.

Piechota, T. C., and J. A. Dracup, 1996: Drought and regional hydrologic variation in the United States: Associations with the El Niño Southern Oscillation. *Water Resour. Res.,* **32,** 1359–1373.

——, F. H. S. Chiew, J. A. Dracup, and T. A. McMahon, 2001: Development of exceedance probability streamflow forecast. *J. Hydrol. Eng.,* **6,** 20–28.

Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.,* **115,** 1606–1626.

Sankarasubramanian, A., A. Sharma, and U. Lall, 2003: Water allocation for multiple uses based on probabilistic reservoir inflow forecasts. *Proc. IAHS-IUGG Meeting,* Sapporo, Japan, IAHS-IUGG, 184–191.

——, ——, and S. Espinueva, 2008: Role of retrospective forecasts of GCMs forced with persisted SST anomalies in operational streamflow forecasts development. *J. Hydrometeor.,* **9,** 212–227.

Schaake, J., and L. Larson, 1998: Ensemble streamflow prediction (ESP): Progress and research needs. Preprints, *Special Symp. on Hydrology,* Phoenix, AZ, Amer. Meteor. Soc., J19–J24.

Sharma, A., 2000: Seasonal to interannual rainfall probabilistic forecasts for improved water supply management: Part 1—A strategy for system predictor identification. *J. Hydrol.,* **239** (1–4), 232–239.

Sicard, E., R. Sabatier, H. Niel, and E. Cadier, 2002: A new approach in space-time analysis of multivariate hydrological data: Application to Brazil's Nordeste region rainfall. *Water Resour. Res.,* **38,** 1319, doi:10.1029/2002WR001413.

Voisin, N., A. F. Hamlet, L. P. Graham, D. W. Pierce, T. P. Barnett, and D. P. Lettenmaier, 2006: The role of climate forecasts in Western US power planning. *J. Appl. Meteor. Climatol.,* **45,** 653–673.

Yao, H., and A. Georgakakos, 2001: Assessment of Folsom Lake response to historical and potential future climate scenarios: 2. Reservoir management. *J. Hydrol.,* **249,** 176–196.

Yeh, W. W. G., 1985: Reservoir management and operations models: A state-of-the-art review. *Water Resour. Res.,* **21,** 1797–1818.