OPTIMIZATION OF DAM OPERATION FOR MAXIMIZING WATER USE AND FLOOD PREVENTION: A CASE OF ANGAT DAM,PHILIPPINES

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***ABSTRACT*:**
Angat dam is the main domestic water resource for metropolitan Manila. Optimal dam operation is very important in avoiding possible conflicts between different stakeholders who utilize water from the dam. There are 3 main functions of the dam: 1.) for irrigation purposes in the surrounding provinces of Angat (Bulacan and Pampanga province); 2.) for hydropower generation and 3.) for domestic water use in Metro Manila. Conflicts between stakeholders for these three functions are rampant. This study aims to minimize some of the water-related non-political issues that usually arise between stakeholders. There are two main priorities of the dam optimization for Angat: 1.) To maximize water use and 2.) to prevent flood. This study explores different cases of 3 typhoons from 2011 (Pedring, Quiel and Ramon) by utilizing 50% priority on preventing downstream flooding and 50% priority on water use. In addition, the effects of changing the weights of the objective function in the dam optimization for each priority is also determined to identify how the error is minimized in the optimization system. This system can be a useful tool in utilizing ensemble forecasts to minimize the effects of floods in the downstream side while maximizing the storage capacity of upstream reservoirs during dam operation.

KEYWORDS: dam optimization, flood prevention, water use

1. INTRODUCTION

Local residents of Metro Manila rely on Angat dam for majority of their domestic water supply. However, with the rapidly growing population, there have been quite rampant occurrences of water shortages (extreme drawdown in Angat reservoir) during the dry season and more frequent flooding in downstream Metro Manila during the rainy season.
According to the IPCC Fourth Assessment Report (2007), the frequency of flood events has increased over most land areas consistent with increases in land surface temperature. This is particularly evident in humid regions affected by tropical cyclones (e.g.Philippines). These typhoons often bring heavy rainfall that can cause severe flooding. A system is needed to reduce flood damage due to heavy rainfall and use water effectively.
Appropriate dam operation can reduce flood peaks and water storage can be done more efficiently. The application of pre-established rule curves is usually limited during extreme flood events (Chang and Chang, 2001). Previous studies on the optimal release systems using hydrological models to assist dam operations have been reviewed (e.g. Yeh, 1985; Labadie, 2004). Because of the recent increase in computational power and real-time data availability, simulation approaches have become feasible and attractive (Wurbs, 1993). Previous studies have been done on the optimization of operating rules for multi-reservoir systems taking advantage of real-coded genetic algorithms (Oliveira and Loucks, 1997; Chen, 2003; Chan, 2008). Studies on areas affected by typhoons in Southeast Asia have focused

on the optimal rule curves like Hoa Binh dam in Vietnam (Ngo, et al., 2007). Customized geographical information system was used to support dam release decisions in Korea (Shim et al., 2002); and studies in Taiwan targeted real-time forecasting for flood control (Hsu and Wei, 2007; Chang and Chang, 2009, Wei and Hsu, 2009).

In the past few years, the accuracy of weather forecasting at the basin scale has improved as a result of more reliable numerical weather prediction models. Precipitation is one of the most difficult weather variables to predict because the atmosphere is highly unstable. However, advanced techniques have enabled reasonable predictions at the regional scale (Golding, 2000; Kryzysztofowicz et al., 2004; Honda et al., 2005). Since precipitation is the main input data for hydrological models, the accuracy of Quantitative precipitation forecast (QPF) is reflected in the streamflow forecast.

In addition, Saavedra et al (2010) succeeded to introduce an ensemble forecast system, based on forecast error evaluation from previous QPF for appropriate dam operation aimed at reducing flood peaks and maximizing water use. A weighting module is used to account for the location, intensity and extension of the error. Both the missing precipitation pattern within contributing areas to dams and information from the surroundings can be considered in the system when calculating the forecast error (FE). FE is defined as the ratio of the forecast to the observed precipitation within the evaluated zone (sub-basins, basin, buffers and whole domain). Once the amplitude of perturbation using the weighting module is defined an ensemble of QPF is generated using quasi-random numbers. The obtained ensemble members force the hydrological model producing an ensemble stream flow. Using a threshold flow at the control point downstream, it is decided whether a particular member requires a special dam operation. If so, a priori independent dam release is activated considering the capability of flood attenuation with each reservoir. A combined objective function is set-up to minimize floods at the control point and maximize reservoir storage. The decision variable is the dam release constrained to the previous forecast's performance. The mean of suggested a-priori release is used as the initial guess. Their upper boundaries are proposed to be the mean plus one standard deviation and the lower boundaries are the mean minus one standard deviation.

Angat dam (constructed in 1961) is a concrete water reservoir embankment hydroelectric dam that supplies up to 97% of raw water requirements for Metro Manila through the MWSS and irrigates about 28,000 hectares of farmland in provinces of Bulacan and Pampanga. The total height of the dam is 131m with a total length of 568m and a base width of 550m. It impounds water from the Angat river through the Angat reservoir (capacity 850MCM). The power station of this dam has 10 vertical shaft turbines including turbines from the main powerhouse with an installed capacity of 256,000kW. Angat dam has a normal high water level of 210m according to the Philippine Atmospheric Geophysical and Service Administration (PAGASA) but during extremely high rainfall events, water level in the dam is maintained at 212m by the National Irrigation Authority (NIA). It has 3 gates opening a total of 1.5m to gradually release water that had accumulated due to incessant rains during typhoons. Downstream in Matictic gauge (17m amsl), a critical limit of 33.3m amsl (3000 cms) was maintained as the water level limit for dam optimization.

There are 3 main functions of Angat dam: 1.) for irrigation purposes in the surrounding provinces of Angat (Bulacan and Pampanga province) (mandate of NIA); 2.) for hydropower generation (mandate of NIA) and 3.) for domestic water use inMetro Manila (mandate of MWSS). In this study, dam operation optimization of Angat dam uses 2 objective functions. 1.) to maximize water use upstream and 2.) to prevent flooding downstream in Metro Manila. Optimal dam operation is very important in avoiding/minimizing possible conflicts between different stakeholders who utilize water from the dam. Although the 2 objective functions do not guarantee that it will satisfy all the functions of Angat dam, it is hoped that this method will give an objective alternative in decision making during extreme events in the basin.

PAGASA has already introduced a radar rainfall measurement system in a numerical weather prediction model for their operational use. By applying the ensemble forecast system based on FE evaluation from previous QPF (Saavedra et al., 2010), flood peaks can be reduced downstream and storage volumes can be maximized in the Angat reservoir.

1.1 Objectives

Priority on water use or priority on flood control are two objective functions that pose a conflict during actual operation. This study aims to minimize some of the water-related, non-political issues that usually arise between stakeholders (local/national government, private sectors, and water users) by attempting to satisfy these 2 priorities of dam optimization. There are 2 main objectives of this study: 1.) To determine how we can keep the dam safe during optimization; and 2.) to determine how much increase of the flood downstream after dam operation optimization.

2. METHODOLOGY

2.1 Input data preparation

2.1.1. PAGASA WRF Forecast for Rainfall

Rainfall forecast data from WRF assimilation by the PAGASA was used to force the hydrological model WEB-DHM. Currently, their system is configured to generate 72-hour forecasts at one hour lead time during extreme events available from 2011-2012. The Global Forecast System (GFS) analyses are used for both the initial conditions and boundary conditions. Verification of the forecast was done by conducting a sensitivity analysis for the 2009 typhoon PARMA. This numerical weather prediction data was compared with observed stations data for case studies of typhoons in 2011 with only 2 out of the 4 available rain gauges operating.

In 2011, from January to December, nineteen (19) tropical cyclones entered the Philippine Area of Responsibility (PAR). The top 10 Philippine Destructive Tropical Cyclones during this year are: Tropical Storm (TS) Bebeng (May 8-11); Typhoon Chedeng (May 20-28); Tropical Storm Falcon (June 21-25), Typhoon Juaning (July 25-28), Typhoon Kabayan (July 28-August 5); Typhoon Mina (August 21-29); Typhoon Pedring (September 24-29); Typhoon Quiel (September 29-October 1); Tropical Depression Ramon (October 10-14); and Tropical Storm Sendong (December 15-18). Typhoon Pedring ranked no.1 in the number of affected families/persions although it came only second (with 85 persons) to Sendong (with 1,257 persons) in terms of the number of casualties.

For this study, typhoon Pedring, typhoon Quiel and tropical depression Ramon are considered as sample case studies.

Tropical Depression Ramon was considered as one of the sample cases in this study. The estimated rainfall amount for Tropical depression Ramon was 5 to 25 mm/hour (moderate to heavy) within the 300km diameter. However, the soil layers during this time are already saturated and the water levels in the dams are above average. Hence, flooding downstream occurred.

Typhoon Pedring (official name: Nesat) was selected since this is one of the most damaging typhoons that affected the country and passed through Angat river basin last 2011. This typhoon entered the Philippine Area of Responsibility (PAR) on September 24, 2011 and moved out of the country on September 28, 2011. It affected 3,545 barangays 312 municipalities, 42 cities in 35 provinces of Regions I, II, III, IV-A, IVB, VI, CAR and NCR. Damage to properties amounted to Php 14,964,489,302.72. Fortunately this typhoon did not cause Angat Dam to spill. However smaller dams such as Ambuklao, Binga, Magat and San Roque had to open their respective gates as the water levels reached their spilling levels. (NDRRMC, 2011)

Typhoon Quiel (official name: Nalgae) is the second typhoon within the week to hit Northern Luzon after typhoon Pedring. Although the intensity of the rainfall is not as high as that of Pedring, the already high water levels and saturated soil layers of the affected areas triggered landslides and flooding.

2.1.2 Ensemble Rainfall Generation

The forecast data is evaluated with observed real time forcing data (hourly rain gauge station data) of the previous time step. A weight table is used to evaluate the error between the two datasets. The evaluated error of the same time period is applied to the next time step prediction. Forecast data from previous time steps are evaluated for the errors. These errors are applied to the next prediction period and used for making ensemble prediction of rainfall for 24 hours. The error adds to the new forecast prediction by PAGASA during the ensemble member generation. Ten (10) ensemble members were formulated to account for the range of errors between observed and forecast data. This ensemble rainfall is incorporated into the hydrological model for flood prediction.

2.2 Operation Rules

2.2.1. Angat Dam Rule Curve

In the cases of Angat dam, plots of historical water levels are given in **Figure 1.** In 2004, the water level dropped to a low of about 168m during the dry season and drastically spiked up to about 217m in November. Fluctuations such as these below and above normal reservoir water levels need to be optimized to avoid possible damages from drought or floods downstream. **Table 1** below shows the current Angat reservoir operating specifications.

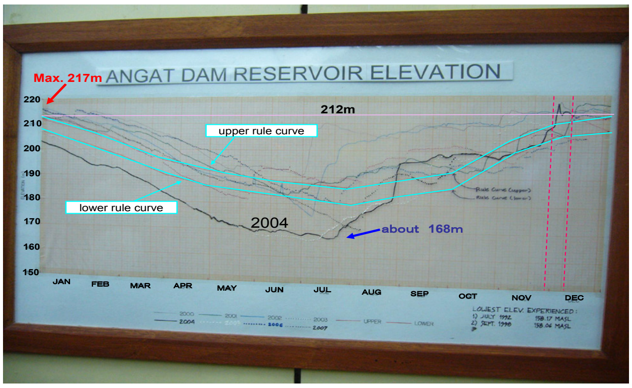

Figure 1. Angat Dam Rule Curve.

Table1 Current Angat Reservoir Specifications.

Specification	Value/limit
Drainage Area	568km^2
Surface Area at NHWL	23km^2
Lowest river elevation	92.5m amsl
Normal high water level	212m amsl
Design Flood water level	219m amsl
Low water level	180m amsl
Lowest flow regulation level	208m amsl

2.2.2. Matictic Gauge Rule

Downstream flood control is determined at Matictic Gauge (approximately 17m amsl). Alerts and alarms are given if the water levels in the river are above three values above mean sea level: 30.59m, 32.15m and 33.3m (See **Table 2** below). Corresponding river discharges are also provided for these levels: 1200m^3/s, 1800m^3/s and 3000m^3/s. For the hydrological simulations, the maximum water level limit is set at 33.3m.

Table 2 Assessment of flow and water level at Matictic gauging station.

Discharge flow	Water level
Alert: 1200m^3/s	30.59m amsl
Alert: 1800m^3/s	32.15m amsl
Critical: 3000m^3/s	33.30m amsl

Flood propagation in Angat dam from Matictic water level station only takes 2 hours and 30 minutes so for the hydrological simulation, the forecast data are given every hour and update of the initial conditions are given every 6 hours as an average initial condition of the propagation times for the dam releases from Angat reservoir.

2.3 Dam Operation Objective Functions for water storage and Flood

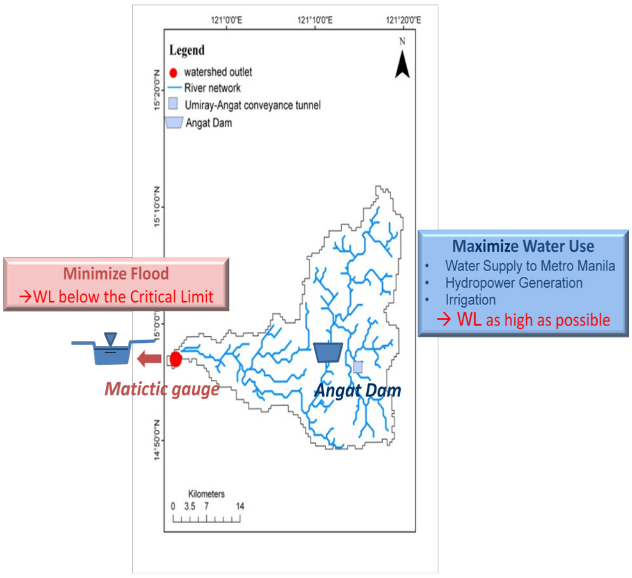

Figure 2. Objective function of dam optimization for Angat.

Both upstream and downstream conditions are considered in the dam optimization by addressing the main functions of the dam: 1.) to supply water to Metro Manila (mandate of MWSS); 2.) to provide irrigation water in surrounding areas (mandate of NIA) and 3. To provide enough hydraulic head for power generation (also mandate of NIA). At the same time avoid conflict between keeping the water level at these high levels and releasing all the water that causes flooding in the downstream areas (specifically to not reach critical limits in Matictic gauge that would translate to flooding in Metro Manila.

3. RESULTS

A previous study (Jaranilla-Sanchez et al., 2012) on the effects of climate change on this basin indicate that heavy precipitation resulting to more frequent flooding will occur in this basin as a result of global warming. To address this, this study explores dam operation optimization as a possible non-structural (soft) adaptation measure for increasing flood risks by modifying existing dam operation. The cases in this study aim to answer 3 questions for the 3 cases:

1. How can we maximize storage in the dam using optimization?

   Typhoon Quiel at 214m water level limit with observed dam release at 50% priority on preventing flood and 50% priority on water storage was used to illustrate this scenario.
2. Can dam optimization work if the initial condition is already very high?

   Tropical depression Ramon at 214m water level limit with observed dam release and 50% priority on flood and 50% priority on water storage was used to illustrate this scenario.
3. What is the effect of varying priorities on the flood and water storage?

   Typhoon Pedring at 212m water level limit with observed dam release with 50% priority on flood and 50% priority on water storage was used to illustrate this scenario.

Using forecast data from PAGASA for 2011-2012 typhoons, 3 typhoon cases (**Figure 3**) are provided in this paper.

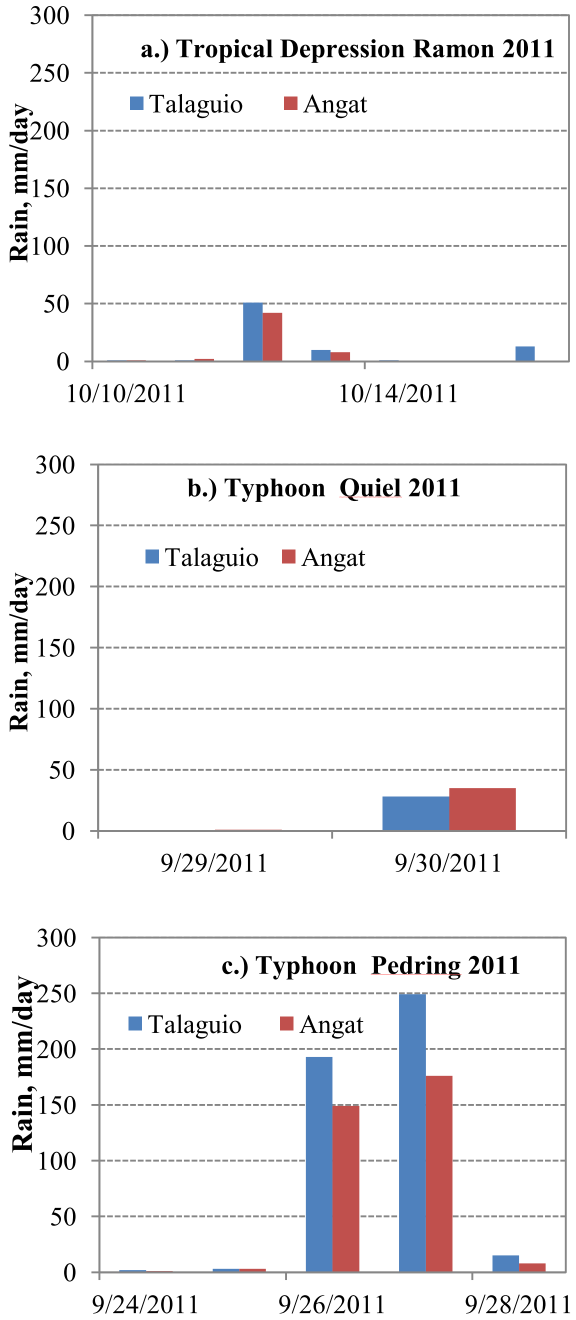

Figure 3. Daily Rainfall for the 3 Typhoons: **a.)** Ramon, **b.)** Quiel and **c.)** Pedring.

For simplicity, **Figures 4**, **5** and **6** are the average of 10 ensemble forecast simulations of upstream and downstream water levels in Angat river basin for typhoon Ramon, Quiel and Pedring.

For the first case, tropical depression Ramon (October 10-October 15, 2011), the daily reservoir (**Figure 4a**) observed water level (light blue line) was already at a very high water level on day 1(October 12) so on the second day, it was unable to keep the desired water level at 212m. For the optimized forecast (pink line), since the initial condition is already above the 212m limit, the limit is increased to 214m and run if the hydrological model is able to maintain the water level at 214m while maintaining the water level downstream below 33m amsl. Some discrepancies were observed on the third day for the daily observed value (light blue) and the water level when the actual daily observed release was released from the dam. Possible reasons for this may be measurement inaccuracies on the daily water level readings.

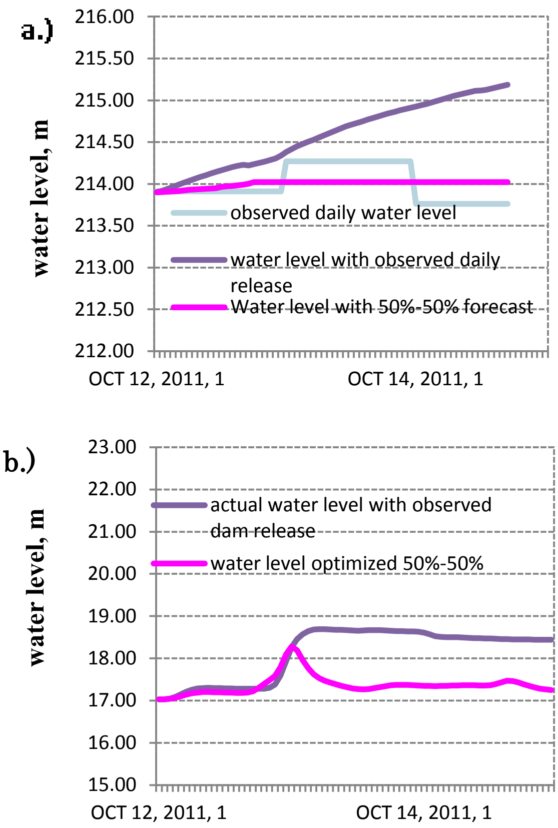

Figure 4. Tropical Depression Ramon 6-hourly average of water level from **a.)** upstream and **b.)** downstream from 50%-50% optimization scheme.

For downstream water level conditions at Matictic (**Figure 4b**), observed daily (converted to hourly) dam release upstream was used to determine the actual water level downstream without dam optimization (purple line). Both the optimized water level and the actual water level did not reach the 33.3m limit that was set for downstream however, it should be noted that the optimized water level showed a sudden increase at the end of day 1as a result of early release before the dam reaches the 214m limit and then maintained a lower water level downstream after the dam reached the limit.

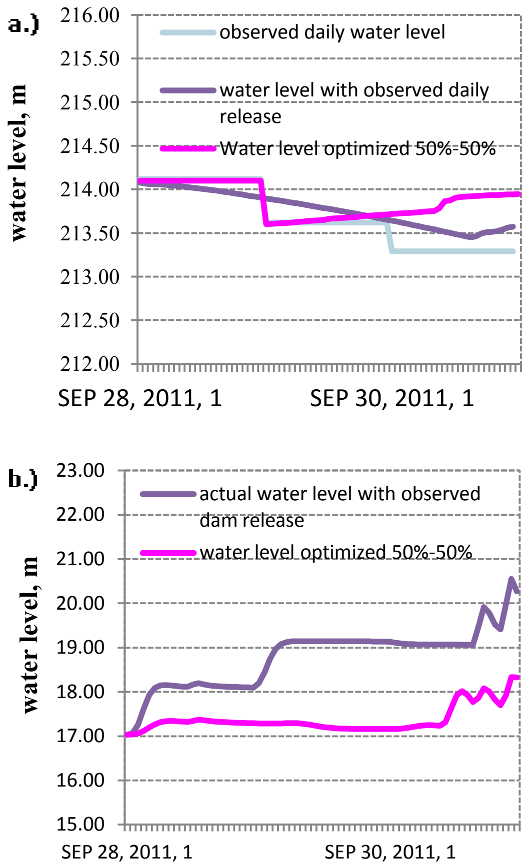

Figure 5. Typhoon Quiel 6-hourly average of water level from **a.)** upstream and **b.)** downstream from 50%-50% optimization scheme.

For the case of typhoon Quiel (September 29-October 1, 2011), this typhoon occurred immediately after typhoon Pedring. Hence, the initial water level is already at a very high level (213.6m). Similar to tropical depression Ramon, the hypothetical limit was set to 214m. The optimized water level was able to maintain the water level of the reservoir below 214m. The observed daily water level however, was operated by releasing on day 2 the water from the dam to avoid the critical limit. Because of this release, a sudden increase in the water level since day 1 at the downstream was observed. The optimized simulation (pink line in **Figure 5a**) was able to maintain water level at the reservoir below the 214m limit while keeping the water level at Matictic below critical (**Figure 5b**). The actual operation on the other hand decided to keep releasing water from the dam to avoid the critical limit. This operation is not ideal because additional water downstream during a typhoon should be avoided to minimize flooding. Fortunately, the water only reached 20.8m (still below the 33.3m critical limit).

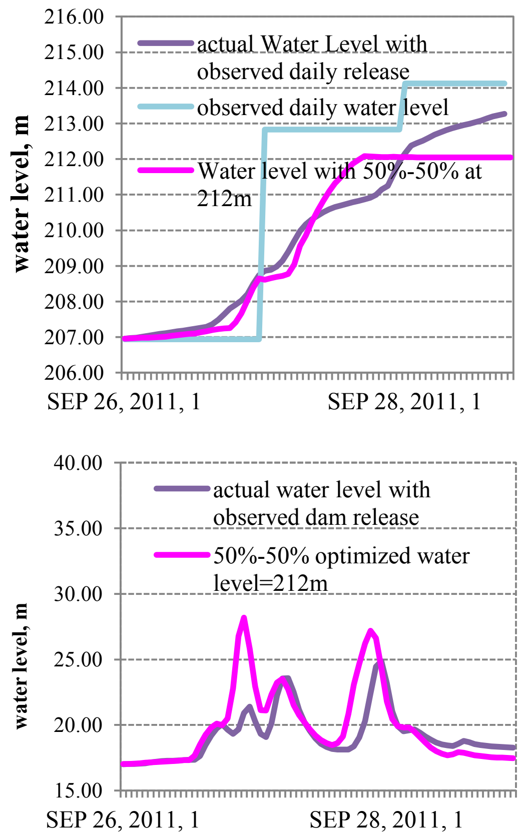

Figure 6. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)** downstream for 50%-50% priority with different reservoir water level limits of 212m from 50%-50% optimization scheme.

The third case is that of typhoon Pedring (September 26-28, 2011) giving equal priority to maintaining water level below the actual set limit of 212m upstream and below 33.3m downstream. The actual 212m limit was considered for this case since the highest water level with observed daily release is actually below 214m.

Starting at water level above 208m, In Figure 6, the light blue line (Figure 6a) is the daily water level during typhoon Pedring. Note that the observed water level was not maintained below the actual recommended 212m limit on the second day of the typhoon. The optimized simulation was able to maintain this limit by releasing water early (pre-release) by the end of day 1. This optimized operation maintains the water level at the 212m limit without compromising the water level at Matictic guage. If a decision similar to this prioritization is given and the forecast given ahead of time, flood damages can be minimized.

4. CONCLUSIONS

This study introduces the forecast system based on forecast error evaluation from previous quantitative precipitation forecast (QPF) issued by PAGASA, for appropriate dam operation. The ensemble method might also be applicable for optimization of dam operation for reducing flood peaks and making maximum use of water using a combined objective function. Optimization of dam operation can be one of the effective measures for adapting to climate change. The decision variable is the dam release constrained to the previous forecast's performance. The system's efficiency is evident in reducing the flood peaks downstream while replenishing/increasing the storage volumes. The results from three events indicate the possible feasibility of the system in real-life dam operation.

5. RECOMMENDATIONS

It is recommended that a prototype of this system for optimization of dam operation towards operational use be implemented through multi-stakeholder collaboration by putting high priorities on:

i. Capability of bias correction for radar rainfall,
ii. Real-time data acquisition capability
iii. Real-time system running capability
iv. Operator training

Additionally, further study is necessary for priority setting and identification of desired dam operation function and rules that will satisfy the actual needs of the end users of Angat dam operation that will avoid conflict between the different stakeholders.

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