CHAPTER 4 Water Supply Analysis and Climate Change Impact Assessment

4.1 Simulation of Stream Flow Under the Effects of Climate Change in the Future

4.1.1 Flood Trends

For each basin, flood trends were identified by ranking the daily discharge from highest to lowest values (7806 values) and by identifying how the top 20 peak discharges compare between the past and future simulated discharges from each of the selected GCM models. Detailed results are further discussed in the succeeding section for each of the 3 basins. However, in all the three, future peak discharges are significantly higher compared with past (1981-2000) peak discharge for all the simulations in the selected models. Qualitatively the increasing trend is expected however, careful consideration in quantification of the increase should be done for water management planning.

4.1.2 Low Flow Trends: Drought Discharge

Low flow trends were determined by ranking each year of the past 20 years (1981-2000) and future 20 years (2046-2065) from highest to lowest, taking the daily average for 365 days and using the average of the 355th day discharge as the drought discharge. This value is used as a basis on how frequent the daily discharge for the past 20 years goes below the value for drought discharge. Results for this analysis were not uniform for all models and for all the basins. However, majority of the models show that base flow goes below drought discharge more frequently in the future simulations. To determine the lower limit for the low flow trend, drought discharge in the 10th percentile (2nd lowest value for the past 20 years of rank 355th) was used to identify how much the drought discharge is expected to be reached in the future. Careful consideration of possible uncertainties and projected wetter future years should be considered when accounting for the quantitative decrease in future baseflow.

4.1.3 Monthly Drought Frequency Trends

For drought quantification, the standard anomaly (SA) index [Jaranilla-Sanchez et al., 2011] was used to categorize droughts based on rainfall and discharge. This index is a modification of the more common standard precipitation index (SPI) [Mckee et al., 1993]. It takes into account the different distribution patterns of the hydrological parameters, normalizes these distribution patterns (from the inputs and outputs of the hydrological model WEB-DHM) and standardizes the normalized distribution. This is then categorized into different drought conditions. **Table 4.1-1** shows the different categories used for quantifying using the Standardized Anomaly (SA) index. This categorization is similar to that used for the Standard Precipitation Index (SPI) for uniformity.

Table 4.1-1. Meteorological conditions considered for the range of SA values [UNL, available in http://www.drought.unl.edu/whatis/indices.htm#spi, 2010]; [Mckee et al., 1993]

SA Values	Meteorological Condition
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-0.99 to 0.99	near normal
-1.49 to -1.0	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

The outputs of WEB-DHM on different basins allow simulation of several hydrological parameters with different land and atmospheric conditions (tropical conditions) that result to varying monthly distribution patterns were considered by fitting a distribution pattern to the monthly hydrological parameter values from the simulated discharge of the WEB-DHM simulations for past and future GCM scenarios (from the 6 selected models) of each basin. This was then transformed to the normal distribution (Walpole, 2000), standardized by taking the anomaly (calculated as the difference of the parameter value from its climatic mean (long-term monthly mean)) and divided by the standard deviation of the transformed parameter.

The main benefit of using SA with WEB-DHM is that the effects of monthly and seasonal differences can be identified by SA, while the quantitative effects of evapotranspiration are integrated into calculations of other parameters using the physically consistent hydrological model WEB-DHM. Another advantage of the SA is the ease with which it can be combined with different parameters in spatially identifying the average effects contributing to drought at the basin scale.

Since the analysis of SA considered only monthly discharges, results show different results for different model-basin combinations (Angat and Pampanga show increases while Kaliwa shows decrease) is considered, changes in SA are mostly from increasing moderately dry conditions and slight fluctuations in extremely dry conditions (details are described in the section below on each basin). This indicates that tropical conditions will very likely prevail in the region in the near future. Rainfall patterns and other intrinsic basin properties will still allow the basin to recover from the projected decreasing base flow. However, timing of this rainfall occurrence which may result to flooding should be analyzed further. Unfortunately, the GCMs cannot be used for predicting the timing of rainfall occurrence in the future. Hence, for this part, it is recommended that real-time forecasting information should be incorporated into future planning.

4.2 Angat River Basin

In this simulation, the Umiray-Angat conveyance is neglected for both past (1981-2000) and future (2046-2065). Changes in peak discharges, drought discharges and evaluation of long-term monthly discharges are evaluated for climate effects on floods and droughts in Angat river basin.

4.2.1 Changes in Overall Stream Regime

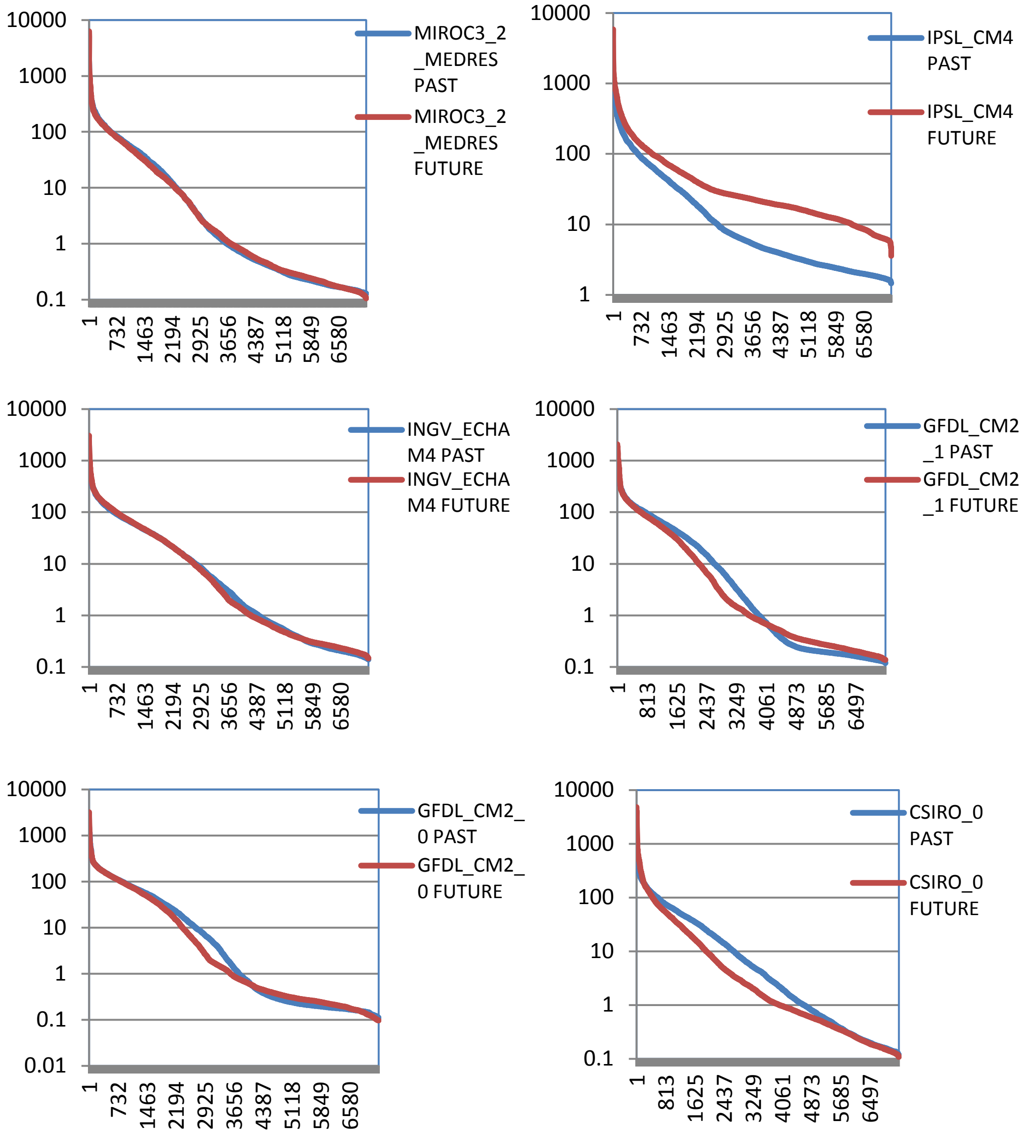


Figure 4.2-1. Climate change trends on discharges for past and future in Angat River Basin in descending order.

Results after ranking the past and future 20 years daily discharge show that similar patterns can be expected in the near future (**Figure 4.2-1**) with four out of the six models indicating a slight decrease in frequency of normal rainfall events. However, looking closely at the highest 20 peak discharge (**Figure 4.2-2**) show that all six of the models project an increase in future peak discharges. Albeit, rank #1 discharge can go from 1.5 to almost 6 times the past values, the remaining 19 peak flows show only a slightly higher (1 times) to double (2 times) of the past peak values. Careful consideration of how much allowance for climate change should be considered when using these values for design.

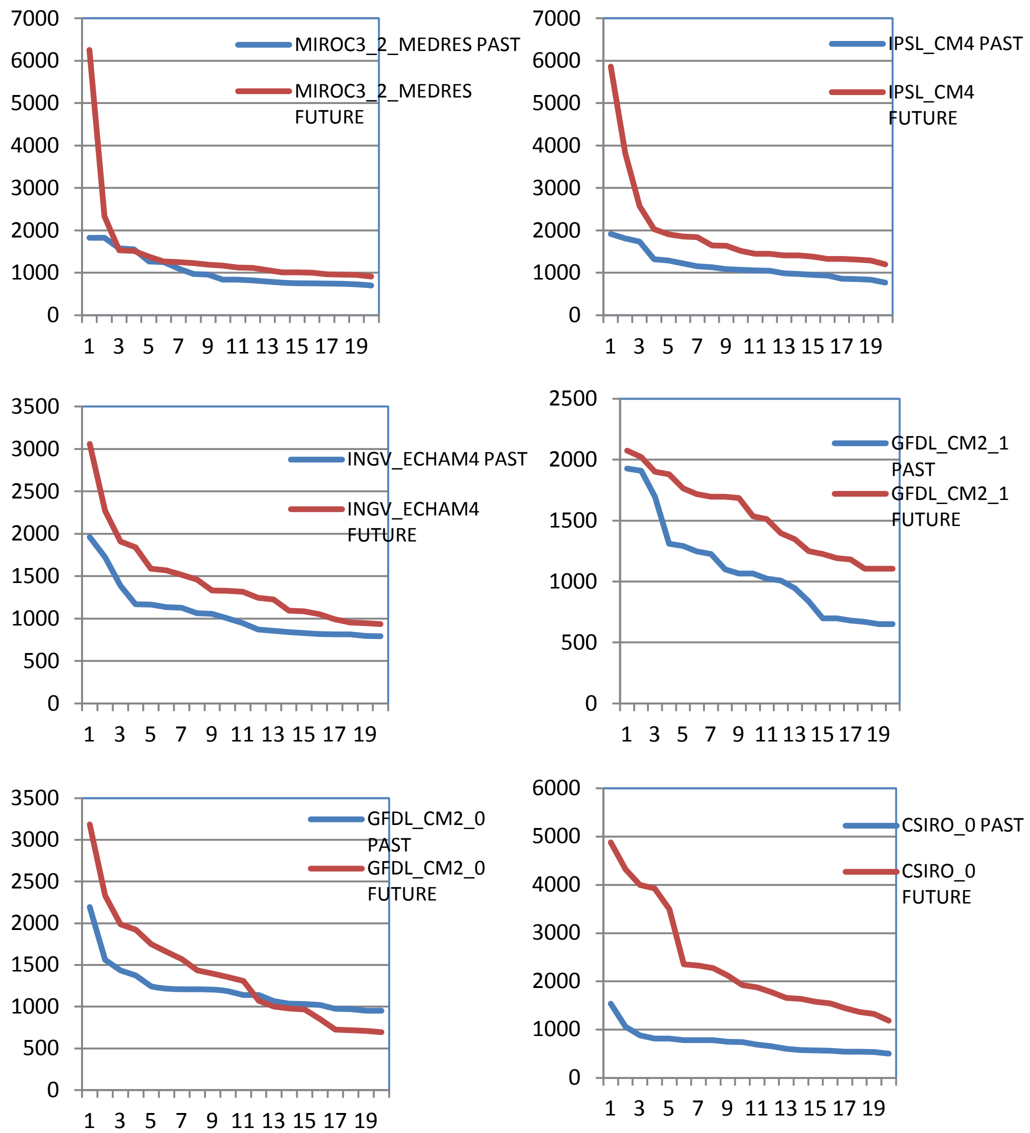


Figure 4.2-2. Climate trends of the highest 20 peak discharges for past and future GCMs in Angat River Basin.

4.2.2 Base Flow Trends with Drought Discharge

Figure 4.2-3 to Figure 4.2-8 show the yearly ranked discharges for the past and future simulations using the 6 selected GCM models. Based on the average of the 355th rank daily discharge, a summary of changes in base flow is given in **Table 4.2-1**. For Angat dam inflow, two out of the six models show much more frequently lower than average drought discharge baseflow (by 1.2 to 1.45 times) while 3 out of the 6 models showed lower than 10th percentile drought discharge (by 3 to 6.5 times) . Three of the models indicate a possibly much higher baseflow in the future. This difference might be due to the rainfall as affected by evapotranspiration rates from the thicker vegetation conditions in the basin. However, careful consideration should be done when using these projected quantities in the future by accounting for possible errors in the input data as well as uncertainties in the model projections.

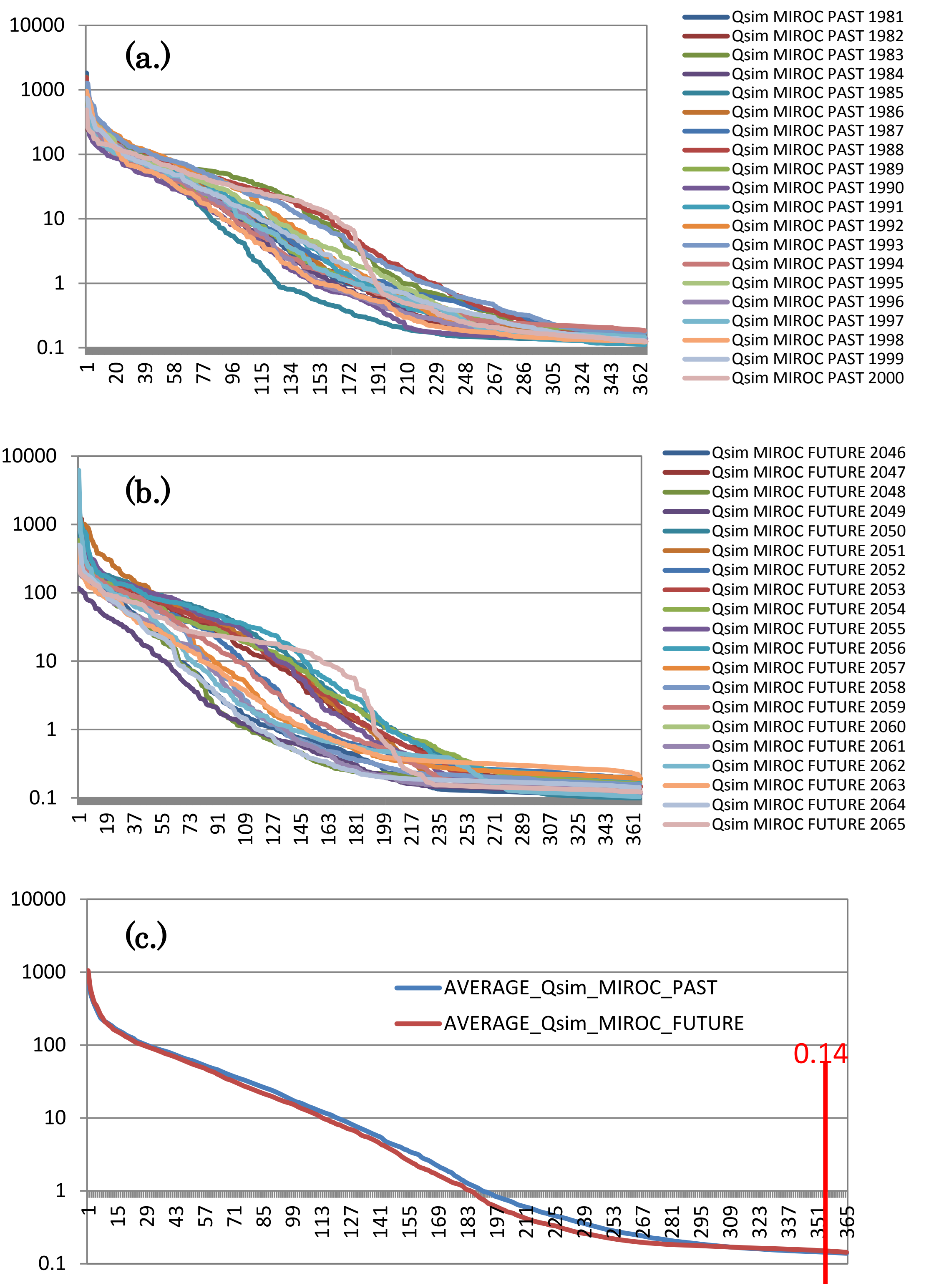


Figure 4.2-3. Discharge for the **a.)** past and **b.)** future 20 years of MIROC_3_2_MEDRES and **c.)** average of the same rank discharge for past (blue) and future(red) with past drought discharge at 355th day rank=0.14m^3/s for Angat Dam inflow

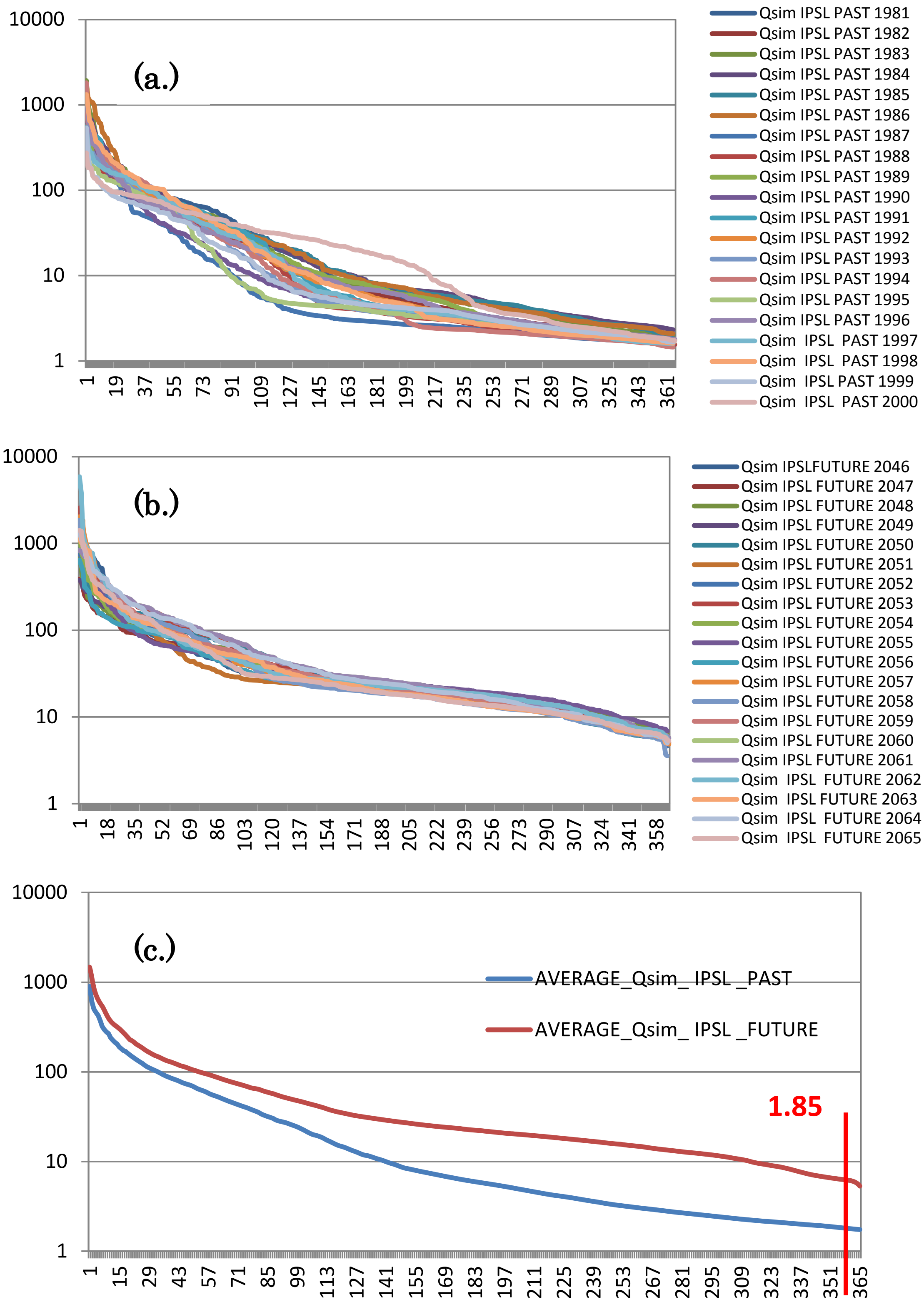


Figure 4.2-4. Discharge for the **a.)** past and **b.)** future 20 years of IPSL and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=1.85m^3/s for Angat Dam inflow.

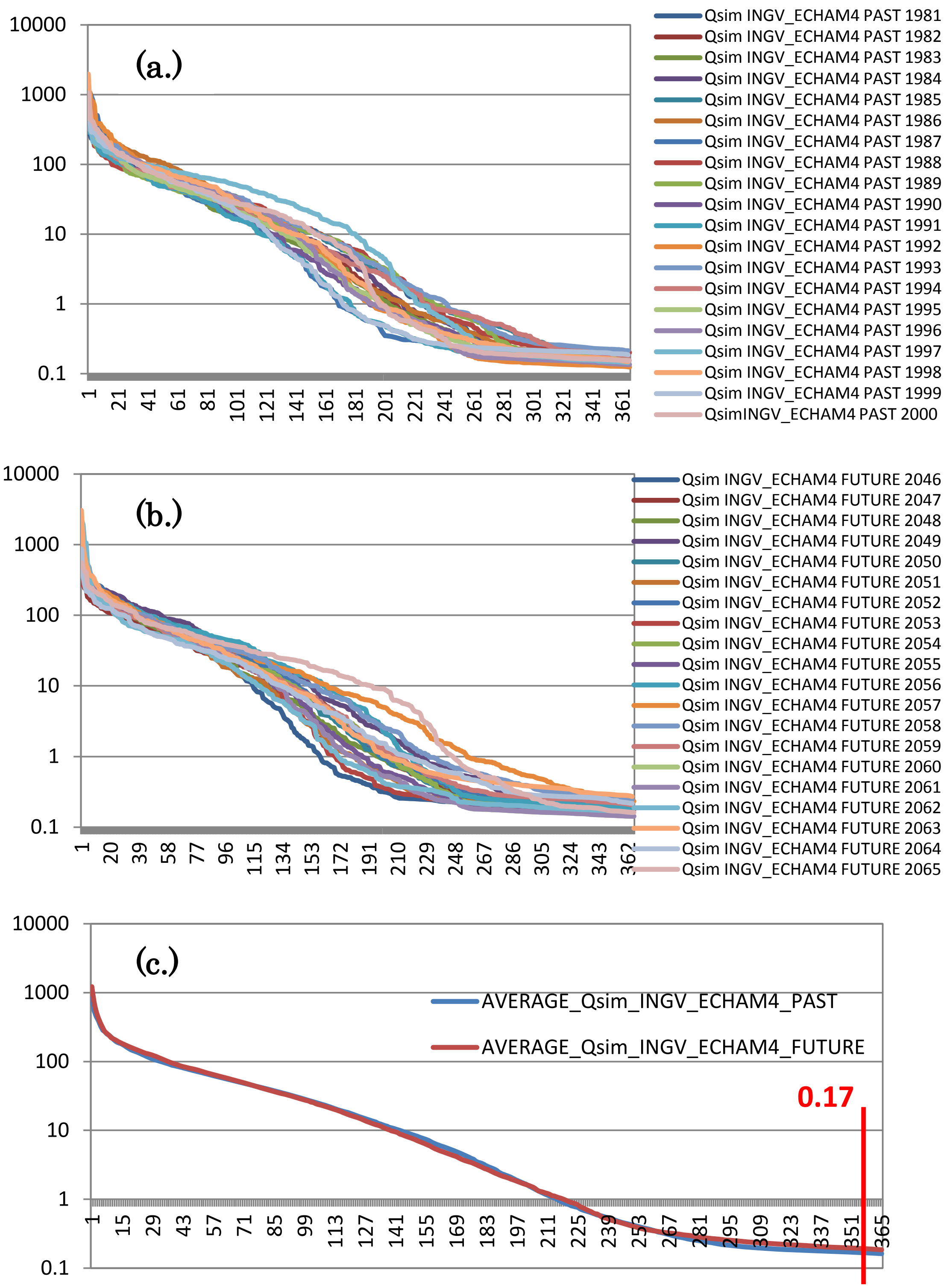


Figure 4.2-5. Discharge for the**.)** past and **b.)** future 20 years of INGV_ECHAM4 and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.17m^3/s for Angat Dam inflow.

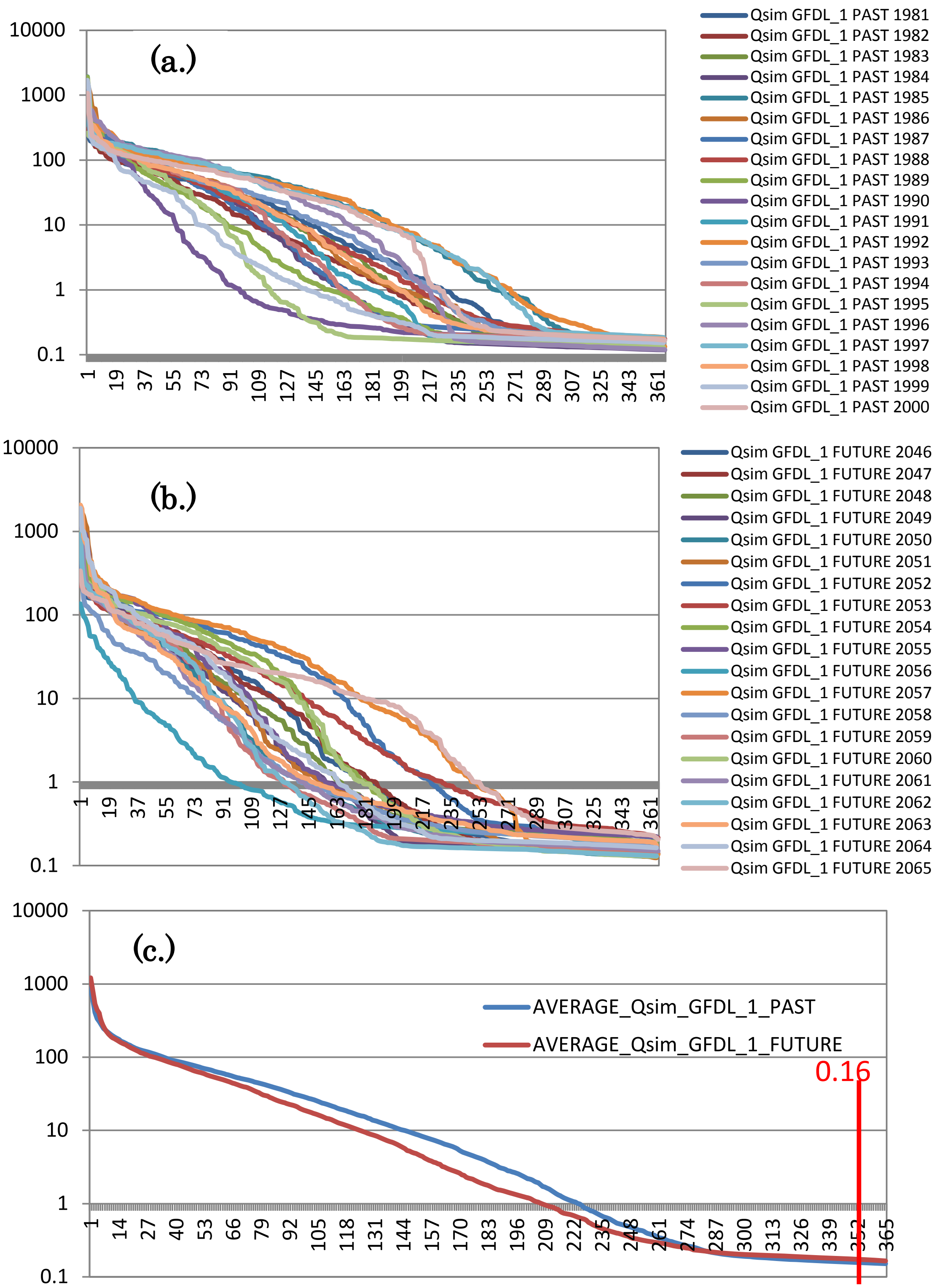


Figure 4.2-6. Discharge for the **a.)** past and **b.)** future 20 years of GFDL_1 and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.16m^3/s for Angat Dam inflow.

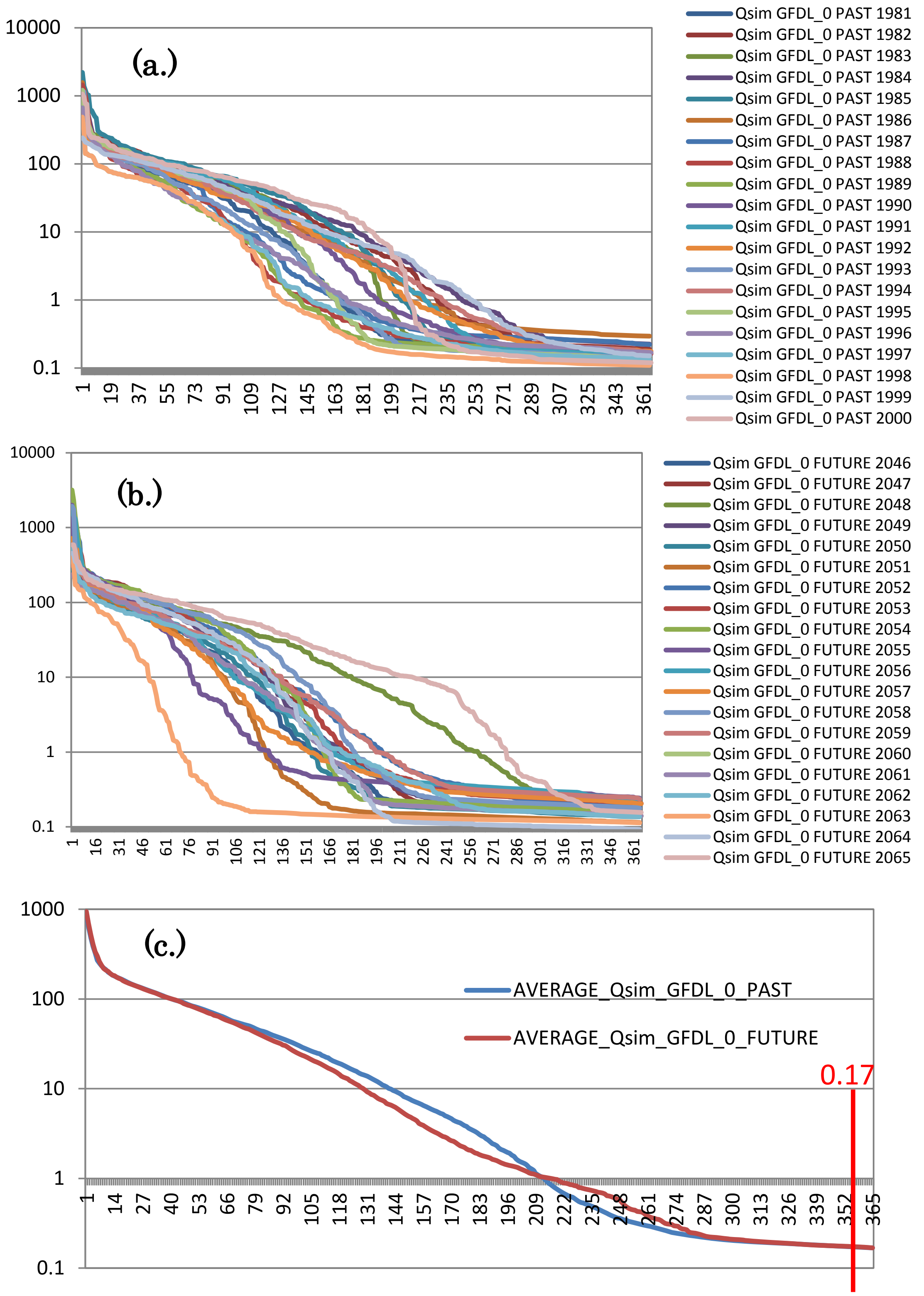


Figure 4.2-7. Discharge for the **a.)** past and **b.)** future 20 years of GFDL_0 **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355^{th} day rank=0.17 m^3/s for Angat Dam inflow.

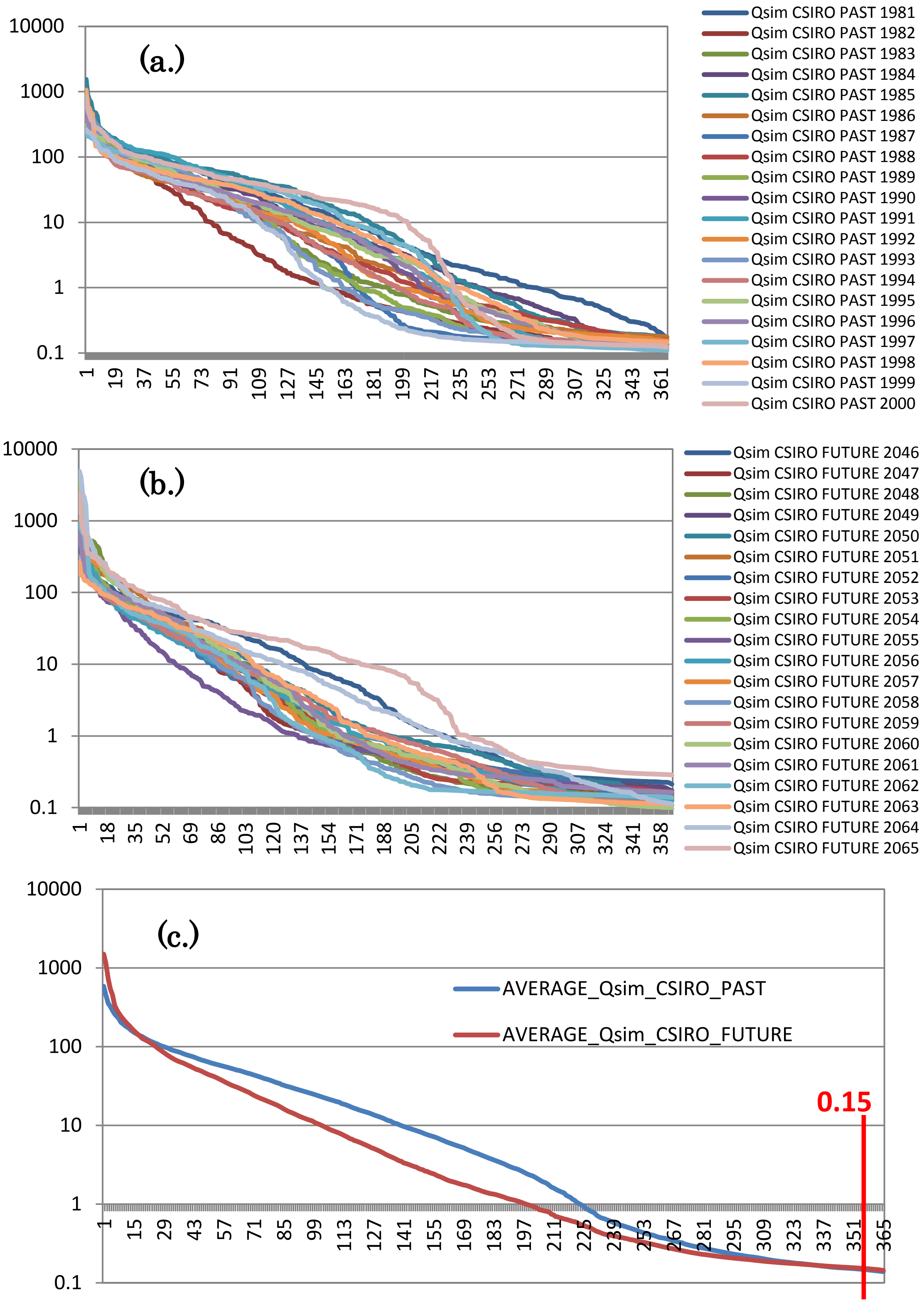


Figure 4.2-8. Discharge for the **a.)** past and **b.)** future 20 years of CSIRO **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.15 m^3/s for Angat Dam inflow.

Table 4.2-1. Summary of Flooding and drought trends in future GCMs for Angat dam Inflows.

GCM Model	Flooding trends average of the 20 highest Peak Flow (m^3/s)		Drought Discharge (m^3/s) (average 355th rank)		# of days/year that baseflow < past drought discharge (average of 355th rank)		Upper Limit of Drought Discharge (m^3/s) 2nd lowest value* of 355th rank		# of days/year that baseflow < past drought discharge (2nd lowest value* of 355th rank)		Longest # of days for each year below average drought discharge		Change in SA (%)		
	Past	Future	Past	Future	Past	Future	Past	Future	Past	Future	Past	Future	ED	SD	MD
MIROC	983.50	1456.98	0.144	0.151	27	34	0.123	0.107	2	13	100	135	--	50	14
IPSL	1149.05	1921.72	1.85	6.46	22	0	1.6	5.939	2	0	59	0	--	--	0
INGV	1070.14	1435.74	0.17	0.194	30	11	0.138	0.156	3	0	104	76	--	-66	25
GFDL_1	1081.93	1550.13	0.156	0.173	39	28	0.123	0.131	1	0	134	88	--	--	-20
GFDL_0	1172.05	1380.76	0.174	0.175	44	64	0.122	0.116	3	13	167	255	-100	50	60
CSIRO	737.92	2342.20	0.15	0.154	37	34	0.13	0.11	5	15	193	191	--	-100	-100

Red=drier in future; more frequent below drought discharge

Blue=wetter in future; less frequently below drought discharge

ED=Extremely Dry condition SD=Severely Dry condition MD=Moderately Dry condition

*There are 20 values from the 355th rank of past 20 years and future 20 years. The 2nd lowest value for past and 2nd lowest value for future is used as upper limit of drought discharge and compared.

4.2.3 Longer duration Droughts- and SA

For simulated dam inflows in Angat, SA projections for each of the selected models show (**Figure 4.2-9** and last three columns of **Table 4.2-1**) that three of the models project an increase in moderately dry conditions, one model indicates similar conditions in the past and in the future while two models show a decrease in future moderately dry conditions. There is a lot of uncertainty in the projections for the longer duration drought for this basin. This means that careful consideration should be done to accurately predict long-term drought effects in this basin especially since drought frequency trends in the near future has a large uncertainty. Preparations for planning should consider both worse-case-scenario (increasing moderately and severely dry conditions) and best case (no change or decreasing dry conditions).

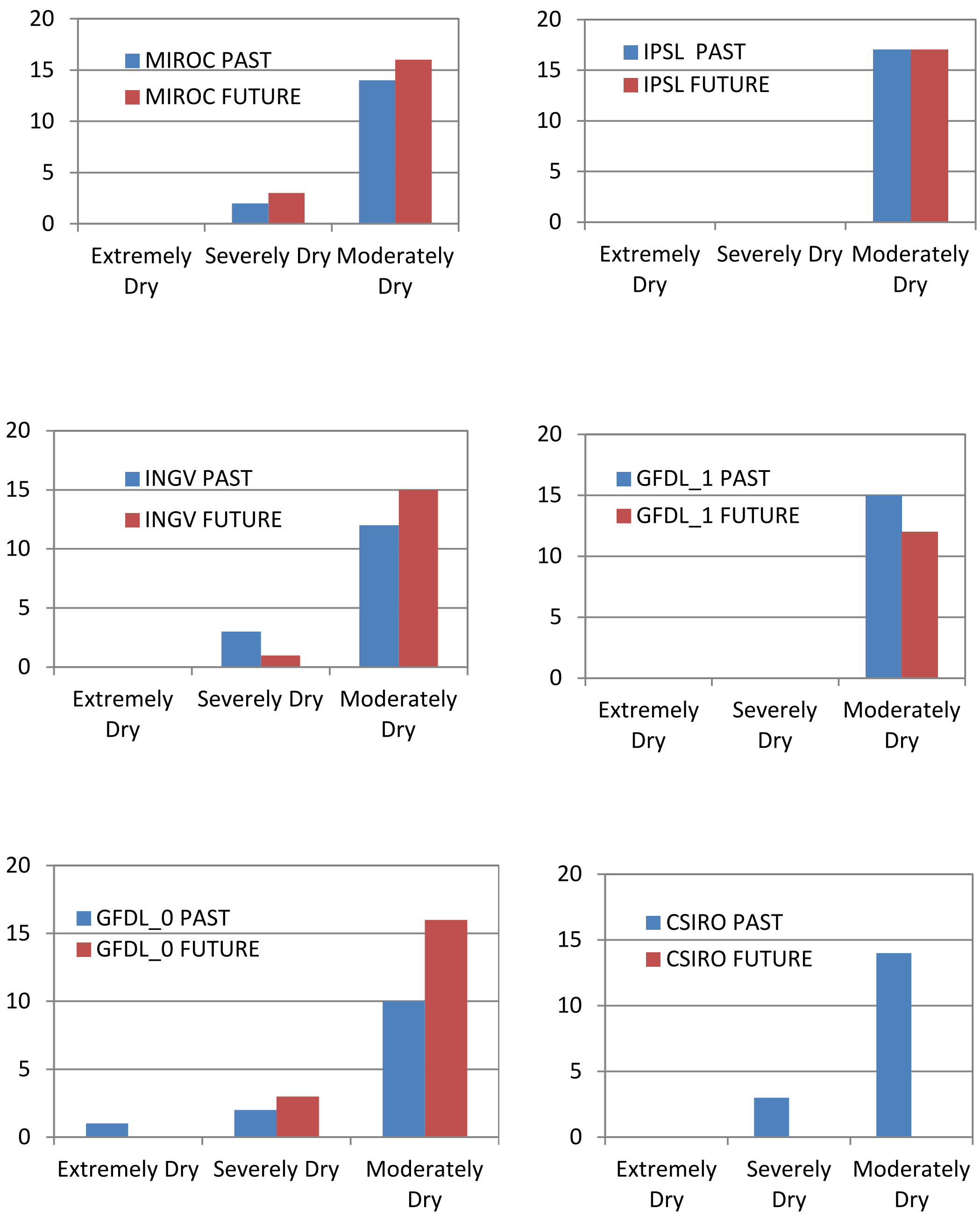


Figure 4.2-9. SA indices for the 6 selected GCM models for Hydrological drought in Angat Dam (based on simulated monthly discharge)

4.3 Kaliwa River Basin

Detailed discussion on streamflow changes in terms of flood peaks, drought discharge and monthly standard anomalies in Kaliwa river basin are given in the succeeding sections.

4.3.1 Changes in Overall Stream Regime

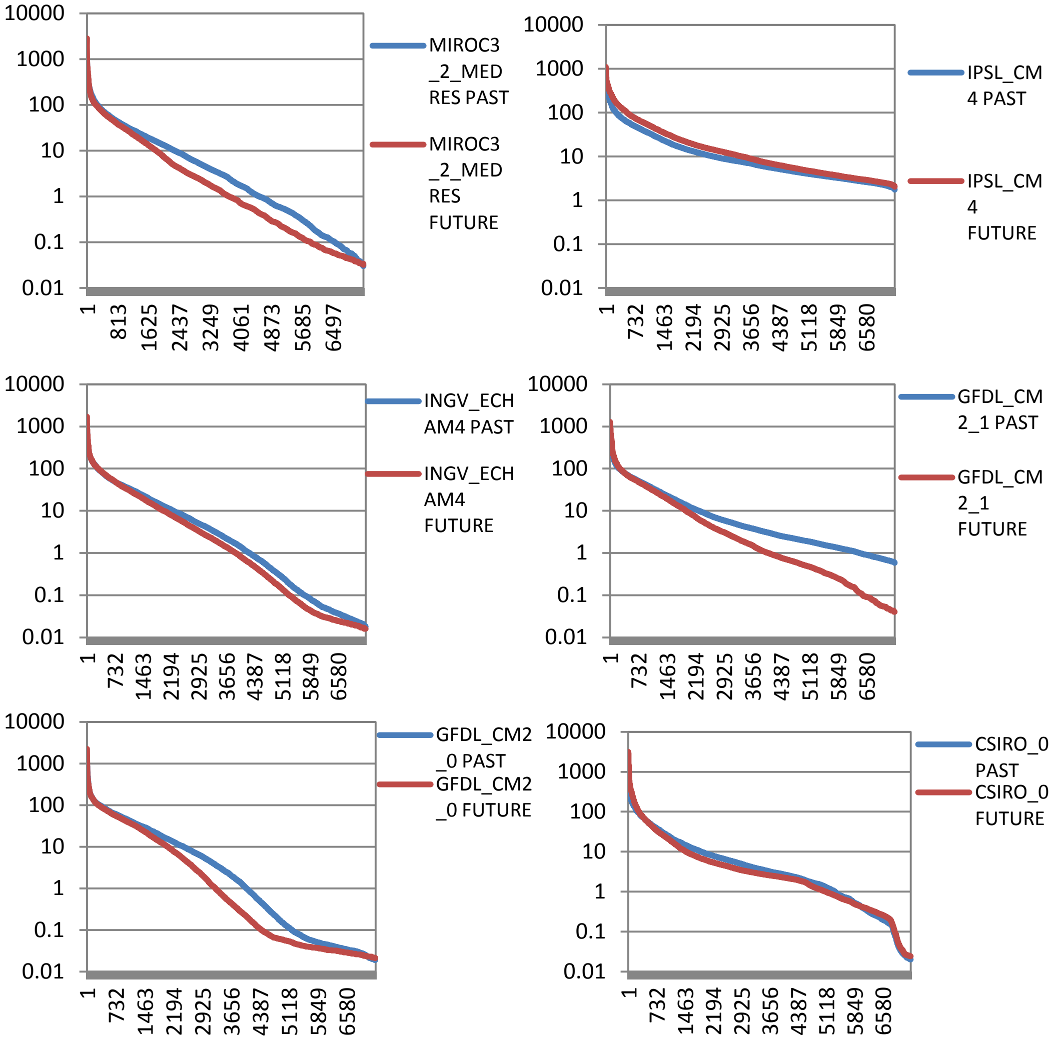


Figure 4.3-1. Climate change trends on discharges for past and future in Kaliwa River Basin in descending order.

Results after ranking the past and future 20 years daily discharge show that similar patterns can be expected in the near future (**Figure 4.3-1**) with 5 out of the 6 models indicating a slight decrease in the occurrence of normal rainfall events. However, looking closely at the highest 20 peak discharges (**Figure 4.3-2**) show that all 6 of the models project an increase in future peak discharges. Albeit, rank #1 discharge can go from similar (1x) up to more than 3x the past values, the remaining 19 peak flows show a slightly higher (1.1x) to double (1.5x) of the past peak values. Careful consideration of how much allowance is given when using these values for design.

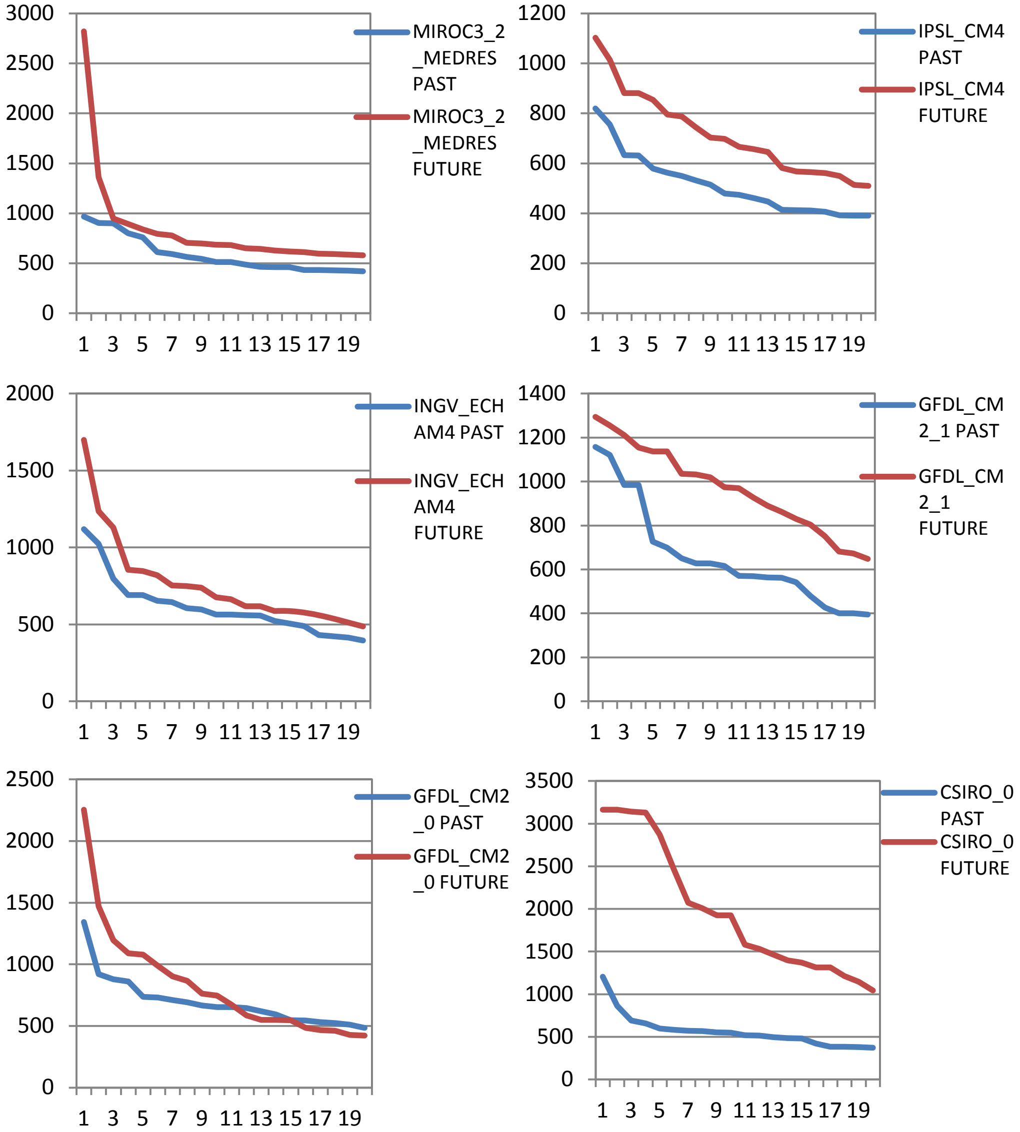


Figure 4.3-2. Climate trends of the highest 20 peak discharges for past and future GCMs in Kaliwa River Basin.

4.3.2 Base Flow Trends with Drought Discharge

Figure 4.3-3 to Figure 4.3-8 show the yearly ranked discharges for the past and future simulations using the six selected GCM models. Based on the average of the 355th rank daily discharge, a summary of changes in baseflow is given in **Table 4.3-1**. For Kaliwa river basin's outlet, four out of the six models show much more frequently lower baseflow (by up to 5 times) in the future as compared to the average drought discharge (range from 0.02 to 2.4 m^3/s). 3 out of the 6 models indicate more frequently lower baseflow than 10th percentile drought discharge by up to 46 times. However, two of the models indicate a possibly much higher baseflow in the future by around 10% to 53%. Similar to Angat river basin, this difference might be due to the rainfall as affected by evapotranspiration from the thicker vegetation conditions in the basin. Again, careful consideration should be employed when using these projected quantities in the future by accounting for possible errors in the input data as well as uncertainties in the model projections.

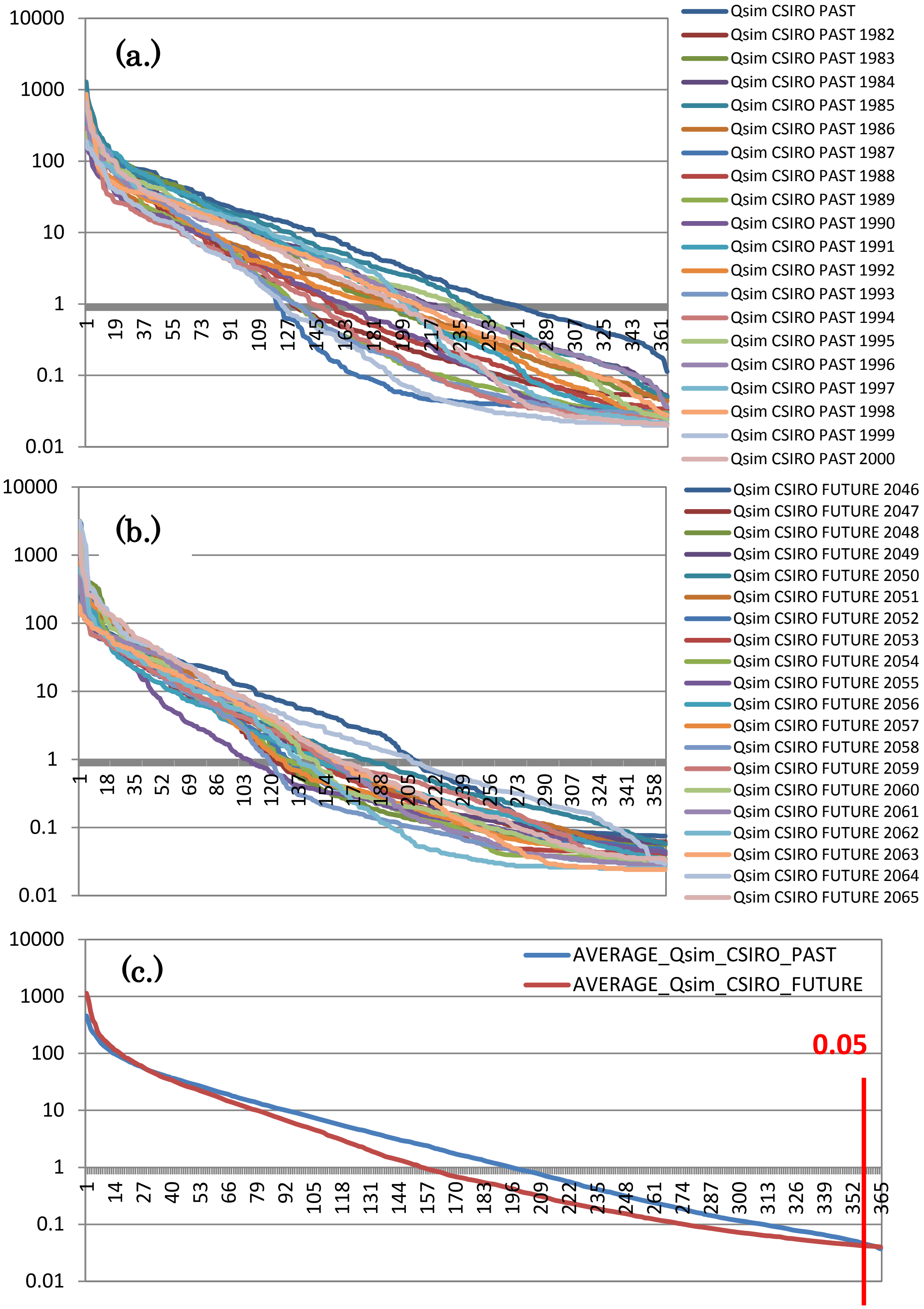


Figure 4.3-3. Discharge for the **a.)** past and **b.)** future 20 years of CSIRO and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.05 m^3/s for Kaliwa River Basin outlet.

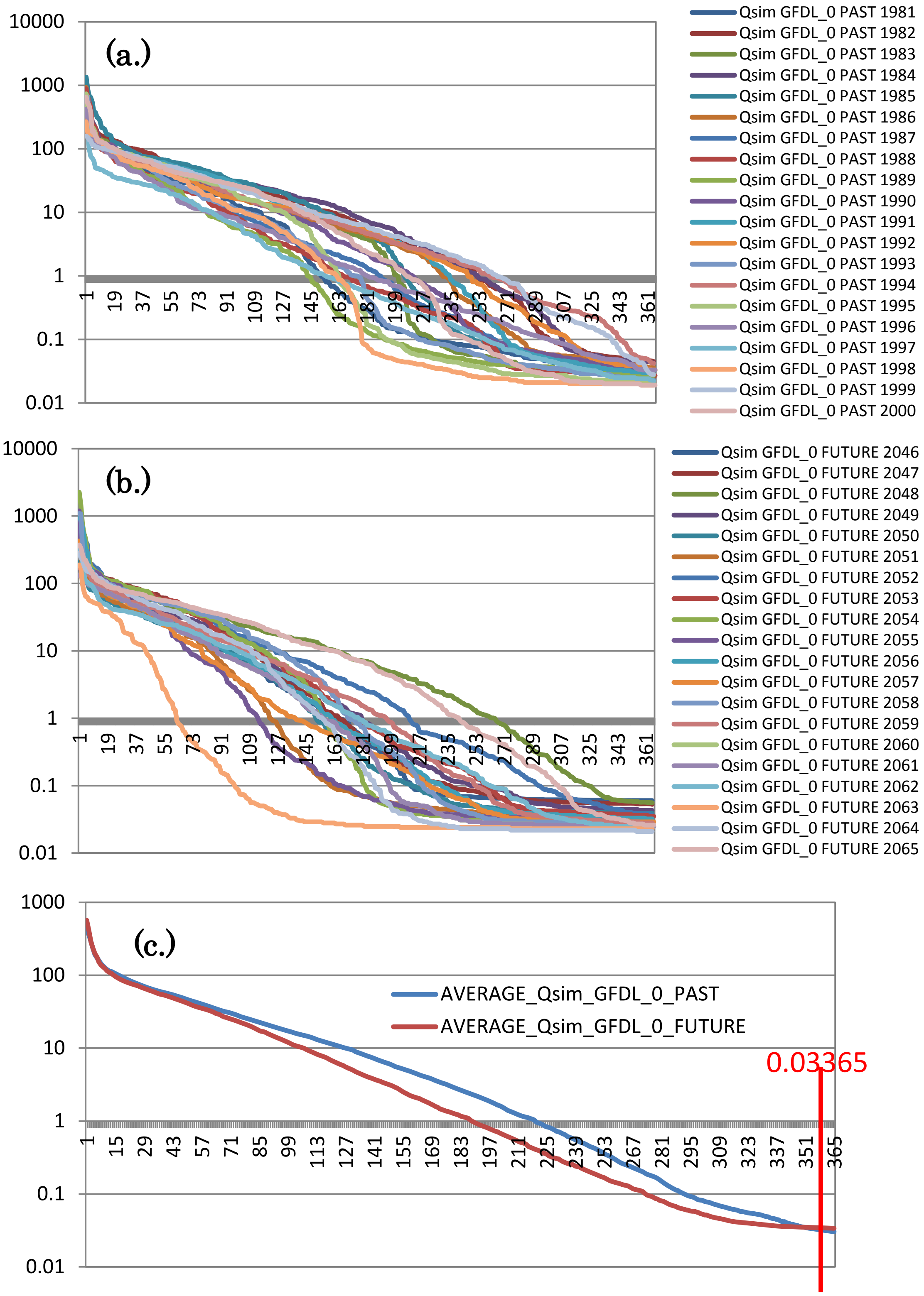


Figure 4.3-4. Discharge for the **a.)** past and **b.)** future 20 years of GFDL_CM2_0 and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.03365 m^3/s for Kaliwa River Basin outlet.

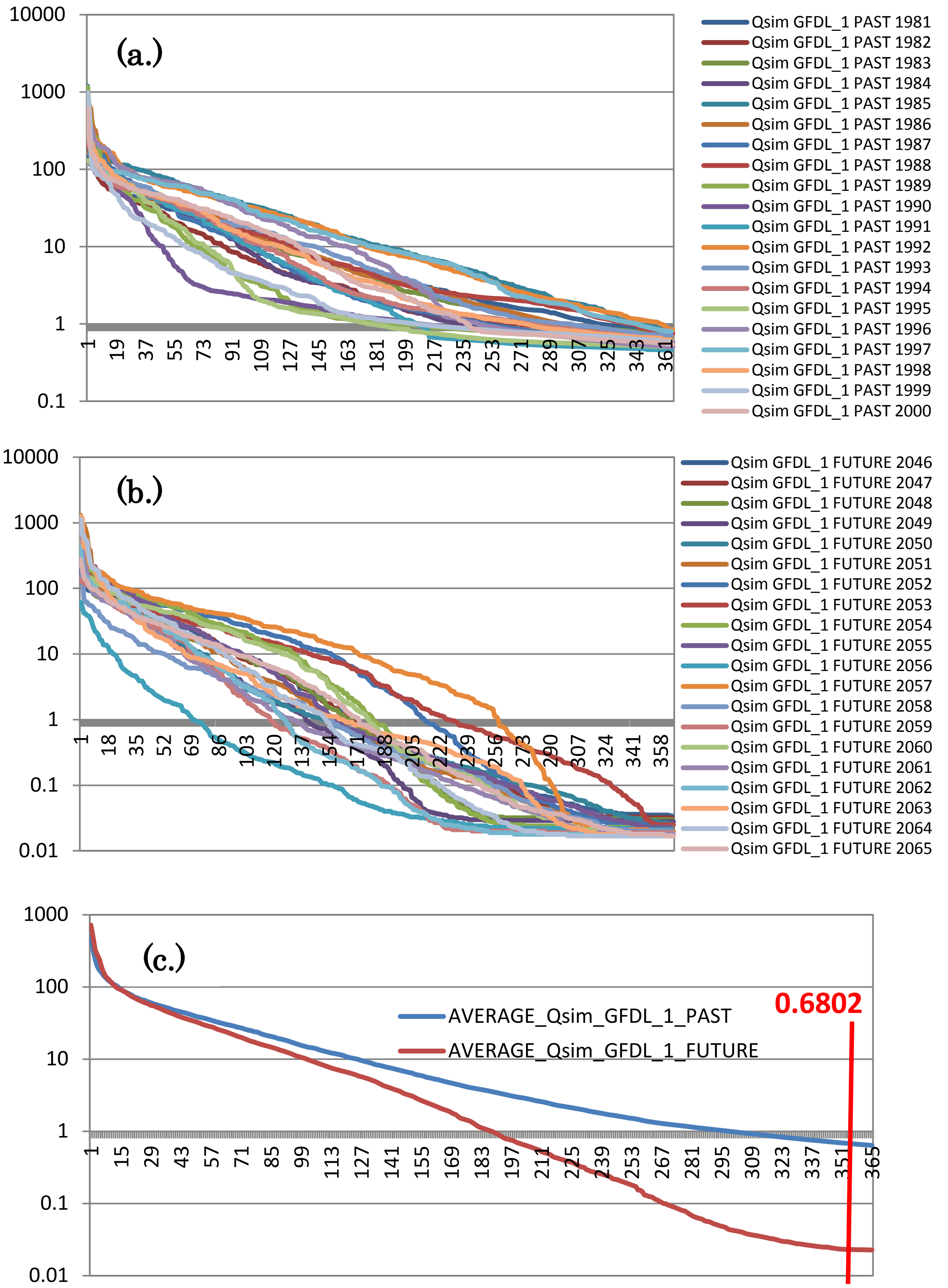


Figure 4.3-5. Discharge for the **a.)** past and **b.)** future 20 years of GFDL_CM2_1 **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.6802 m^3/s for Kaliwa River Basin outlet.

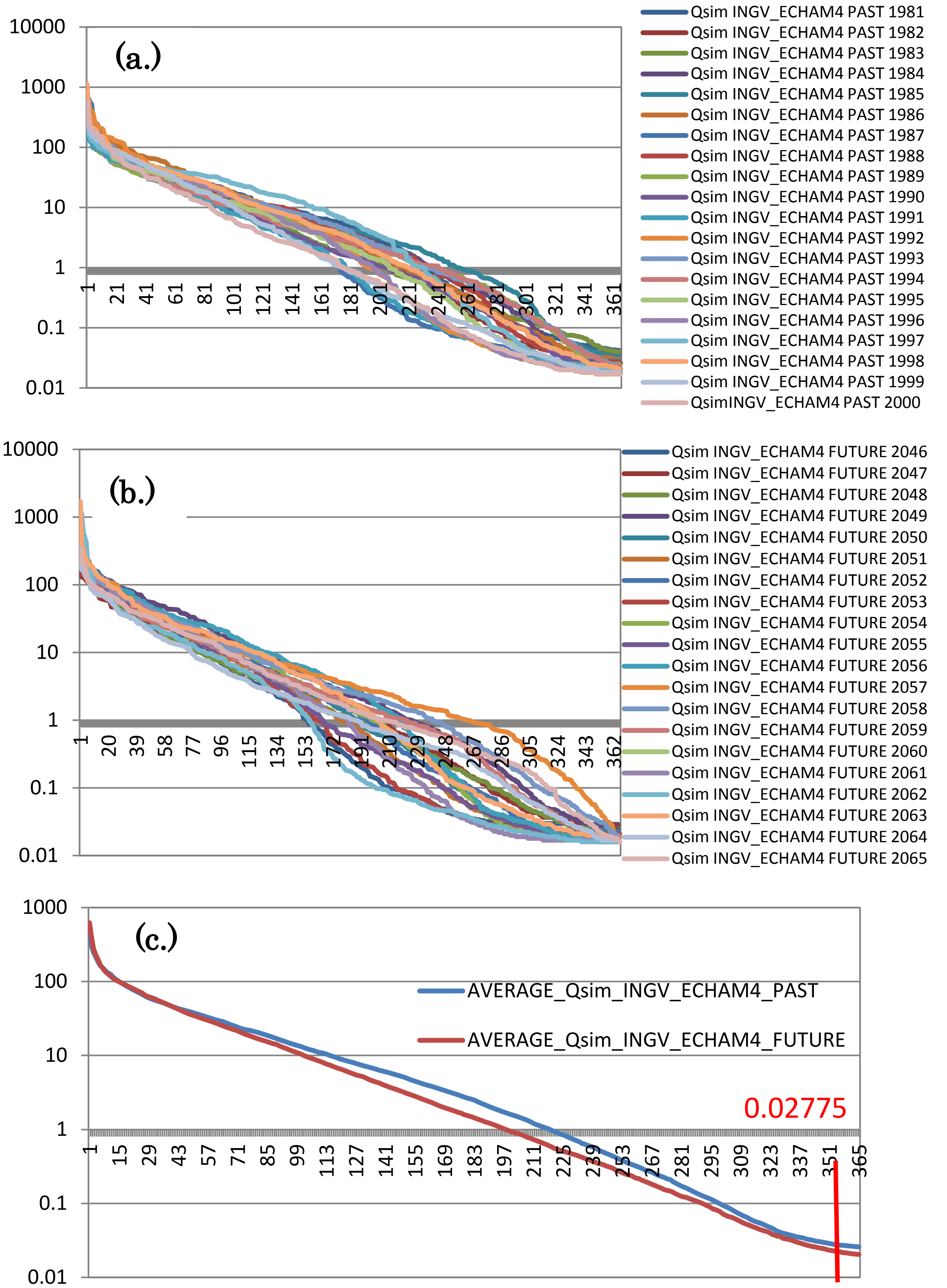


Figure 4.3-6. Discharge for the **a.)** past and **b.)** future 20 years of INGV and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.02775 m^3/s for Kaliwa River Basin outlet.

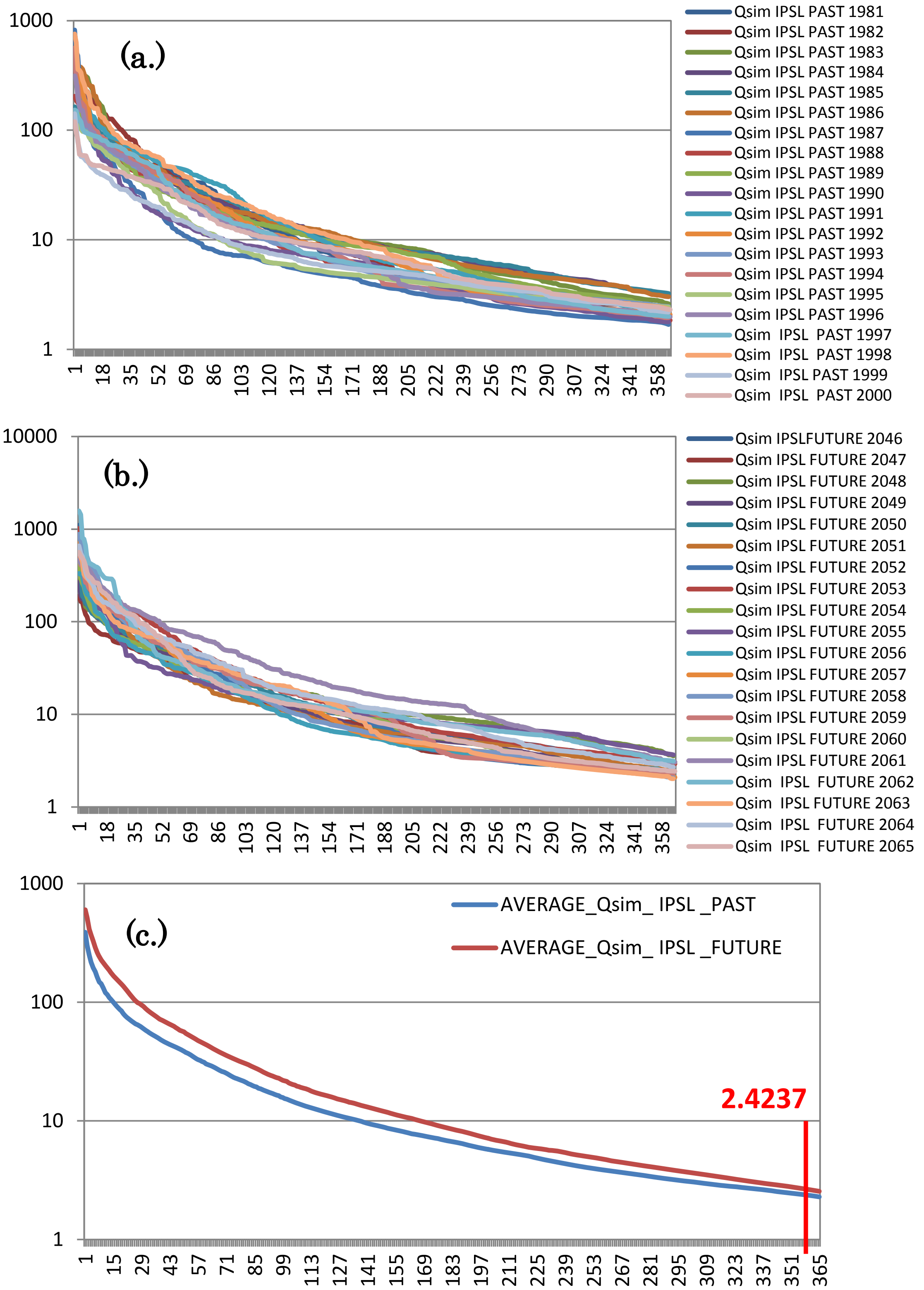


Figure 4.3-7. Discharge for the **a.)** past and **b.)** future 20 years of IPSL and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=2.4237 m^3/s for Kaliwa River Basin outlet.

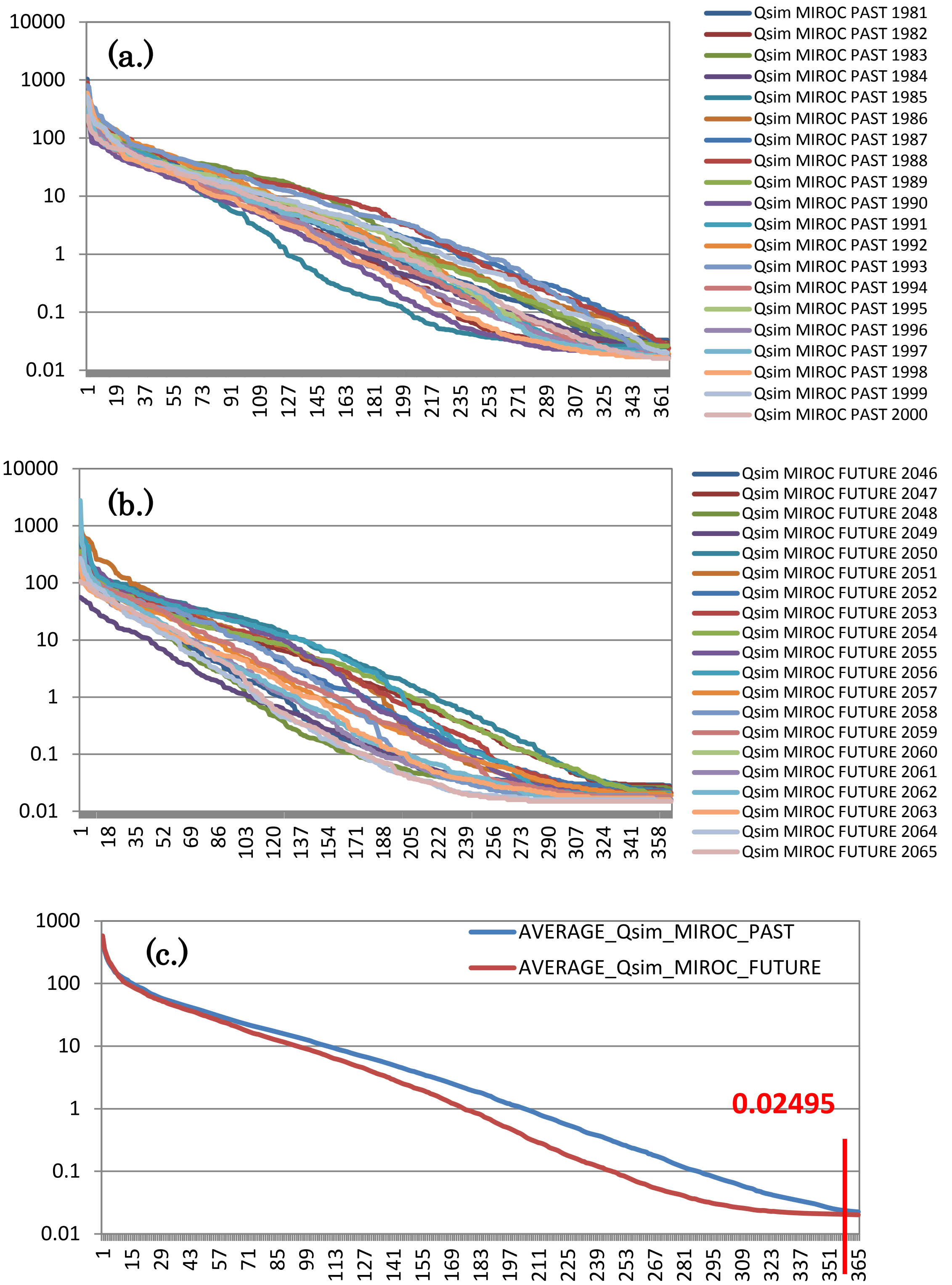


Figure 4.3-8. Discharge for the **a.)** past and **b.)** future 20 years of MIROC **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=0.025 m^3/s for Kaliwa River Basin outlet.

Table 4.3-1. Summary of drought trends from GCMs for Kaliwa river basin.

GCM Model	Flooding trends average of the 20 highest Peak Flow (m^3/s)		Drought Discharge (m^3/s) (average 355th rank)		# of days/year that baseflow < past drought discharge (average of 355th rank)		Upper Limit of Drought Discharge (m^3/s) 2nd lowest value* of 355th rank		# of days/year that baseflow < past drought discharge (2nd lowest value* of 355th rank)		Longest # of days for each year below average drought discharge		Change in SA (%)		
	Past	Future	Past	Future	Past	Future	Past	Future	Past	Future	Past	Future	ED	SD	MD
MIROC	588.17	837.90	0.025	0.021	26	60	0.017	0.016	1	12	79	139	--	-50	-15
IPSL	512.57	841.53	2.42	2.73	27	12	1.857	2.201	2	0	99	38	--	--	0
INGV	612.31	762.52	0.028	0.023	22	45	0.018	0.016	1	7	60	91	--	-66	-8
GFDL_1	624.19	942.52	0.68	0.023	38	192	0.515	0.017	4	184	151	286	--	--	-26
GFDL_0	691.82	825.65	0.034	0.035	34	61.1	0.02	0.023	1	0	133	233	--	-66	0
CSIRO	592.94	1806.19	0.05	0.043	55	49	0.021	0.025	1	0	157	149	--	--	-100

Red=drier in future; more frequent below drought discharge

Blue=wetter in future; less frequently below drought discharge

ED=Extremely Dry condition SD=Severely Dry condition MD=Moderately Dry condition

*There are 20 values from the 355th rank of past 20 years and future 20 years. The 2nd lowest value for past and 2nd lowest value for future is used as upper limit of drought discharge and compared.

4.3.3 Longer Duration Droughts-Using SA

In Kaliwa, monthly drought projections are expected to either have similar conditions as in the past or decrease as shown in **Figure 4.3-9** and last 3 columns of **Table 4.3-1** for all models. This is a good indication that the rainfall effects and the evapotranspiration effects within the basin are still favorable enough for the basin to be able to rebound from the long term effects of droughts. However, since there is still the possibility of baseflow reaching drought discharge levels more frequently in the future, careful planning of water storage and possibly dam operation inclusion (dam building)) should be considered to manage this tendency.

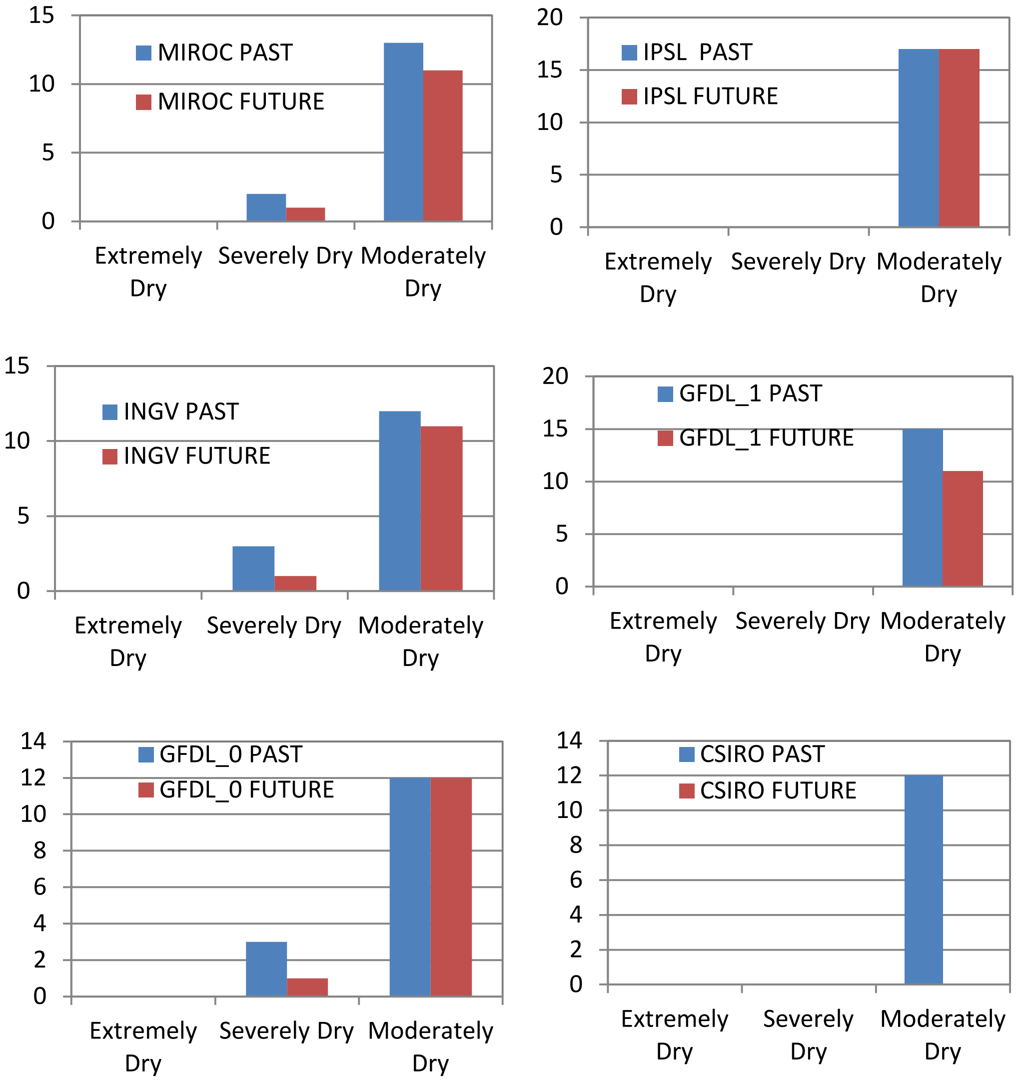


Figure 4.3-9. SA indices for the 6 selected GCM models for Hydrological drought in Kaliwa River Basin outlet (based on simulated monthly discharge)

4.4 Pampanga River Basin

Detailed discussion on streamflow changes in terms of flood peaks, drought discharge and monthly standard anomalies in Pampanga river basin are given in succeeding sections.

4.4.1 Changes in Overall Stream Regime

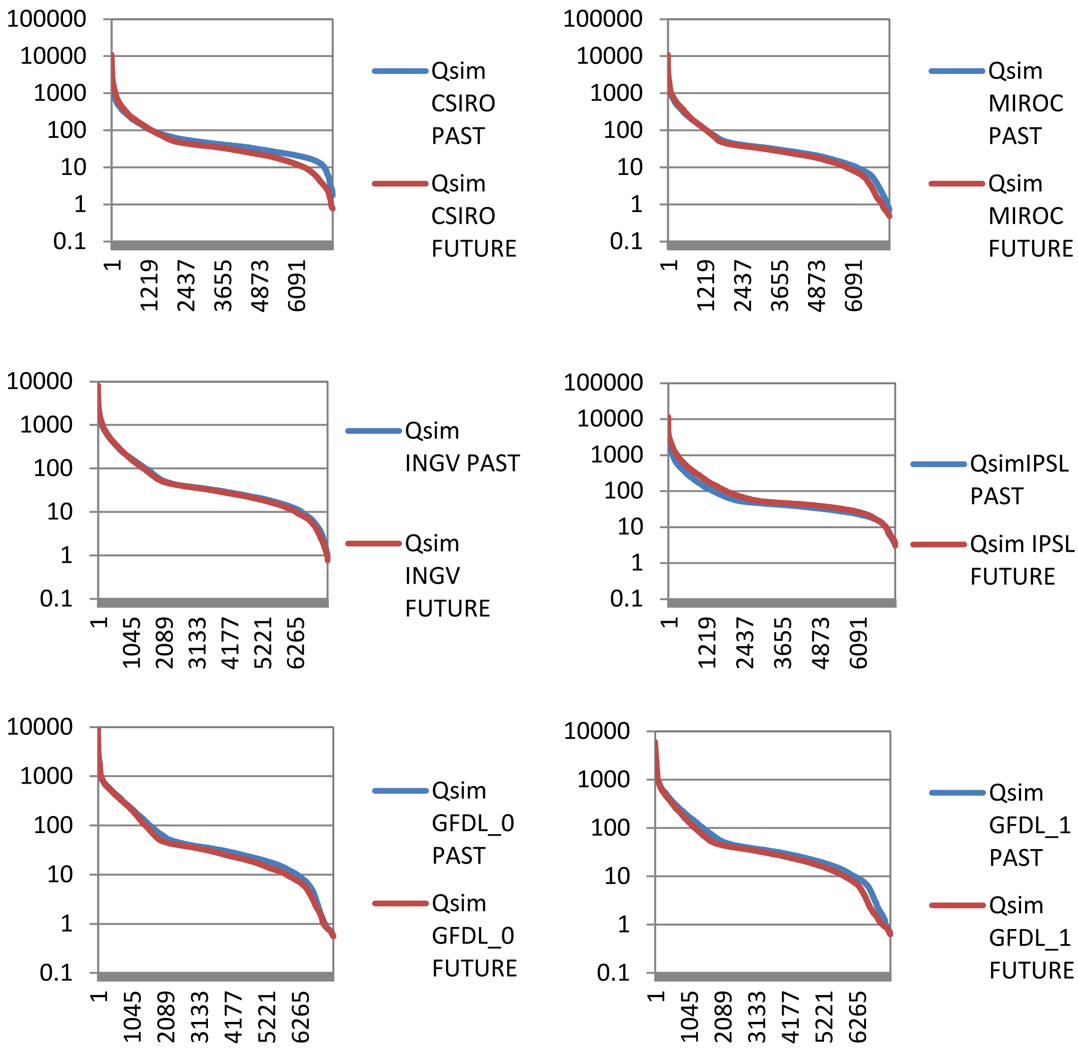


Figure 4.4-1. Climate change trends on discharges for past and future in San Isidro gauge of the Pampanga River Basin (in descending order).

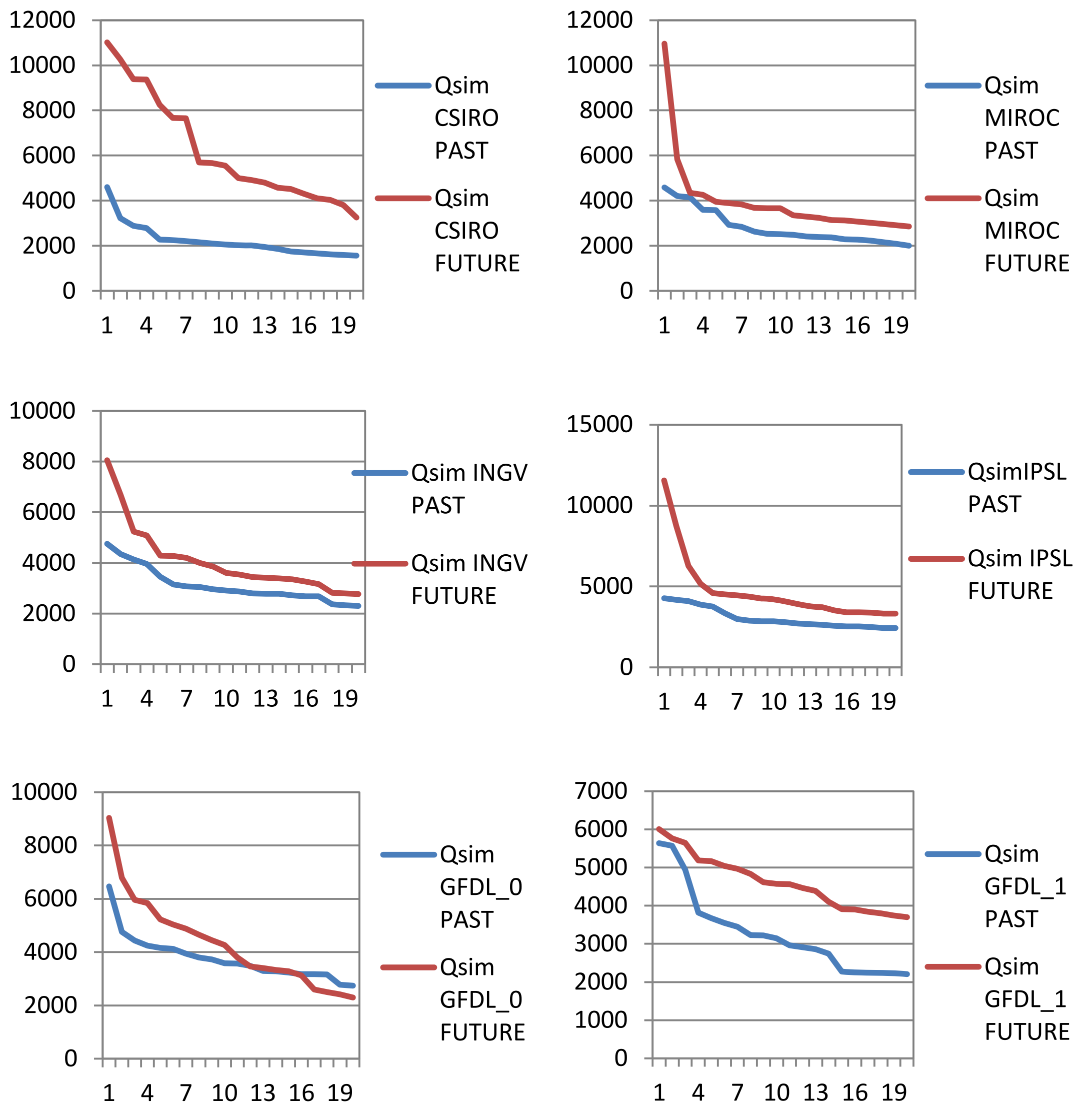


Figure 4.4-2. Climate trends of the top 20 peak discharges for past and future GCMs in San Isidro gauge of Pampanga River Basin.

Similar to results in Angat and Kaliwa river basin's, results after ranking the past and future 20 years daily discharge in Pampanga river basin (figures show flow from downstream San Isidro Gauge) show that similar patterns can be expected in the near future (**Figure 4.4-1**) with 5 out of the 6 models indicating a slight decrease in the occurrence of normal rainfall events. However, looking closely at the top 20 peak discharge (**Figure 4.4-2**) show that all 6 of the models project an increase in future peak discharges. Rank #1 discharge can go from 1.5x up to almost 2x the past values, the remaining 19 peak flows show a slightly higher (1x) to 1.5x the past peak values. Careful consideration of how much allowance is given when using these values for design.

4.4.2 Base Flow Trends with Drought Discharge

Figure 4.4.-3 to Figure 4.4-8 show the yearly ranked discharges for the past and future simulations using the 6 selected GCM models. Based on the average of the 355th rank daily discharge, a summary of changes in base flow is given in **Table 4.4-1**. For San Isidro Gauge, 5 out of the 6 models show much more frequently lower base flow (lower by 20% up to 60%) in the future as compared to the drought discharge (range from 3.6 to 12.7 m^3/s). Although it is imperative from the results that base flow should be managed when planning for the near future, careful consideration should be integrated when using these projected quantities in the future by accounting for possible errors in the input data as well as uncertainties in the model projections.

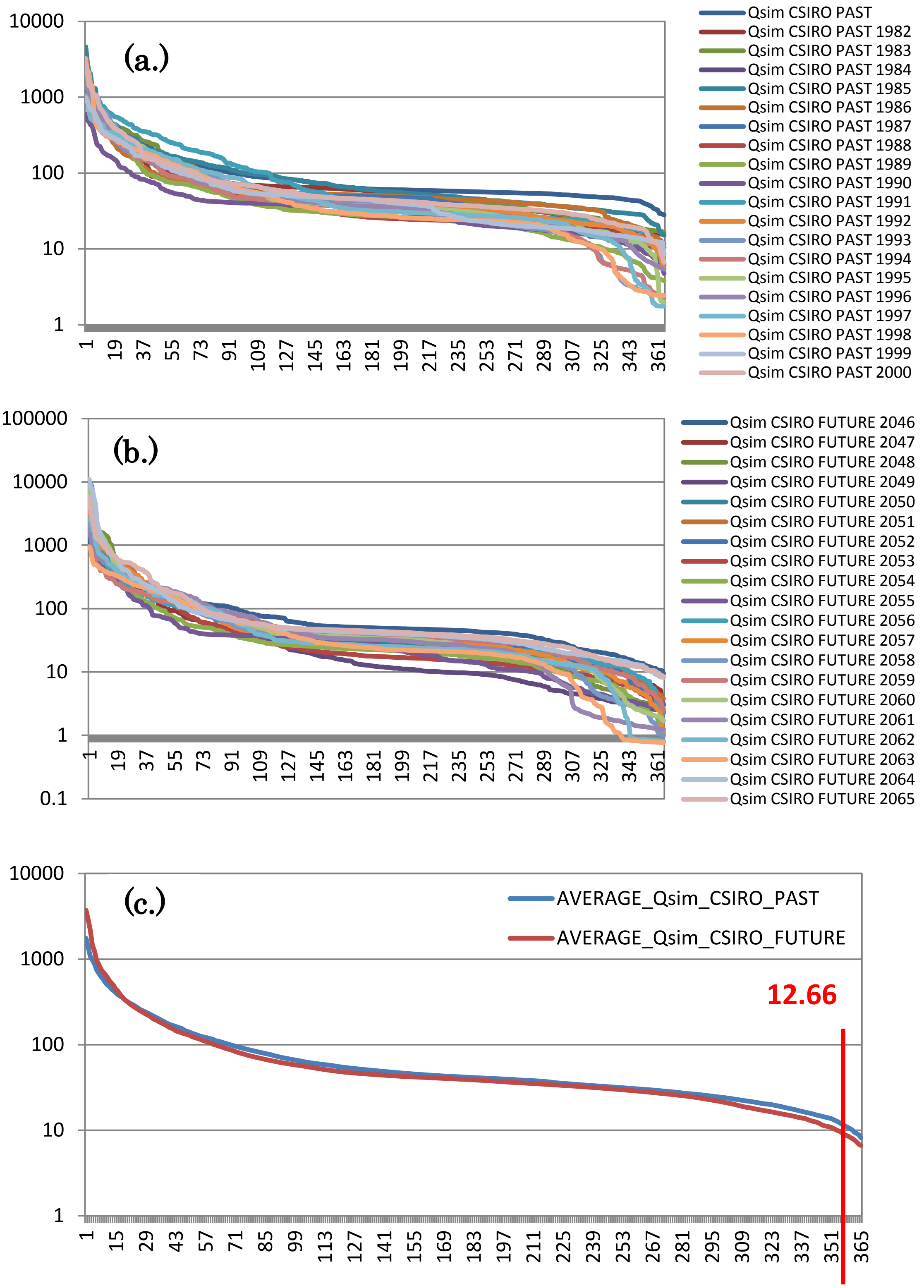


Figure 4.4-3. Discharge for the **a.)** past and **b.)** future 20 years of CSIRO and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=12.66 m^3/s for San Isidro of Pampanga River Basin.

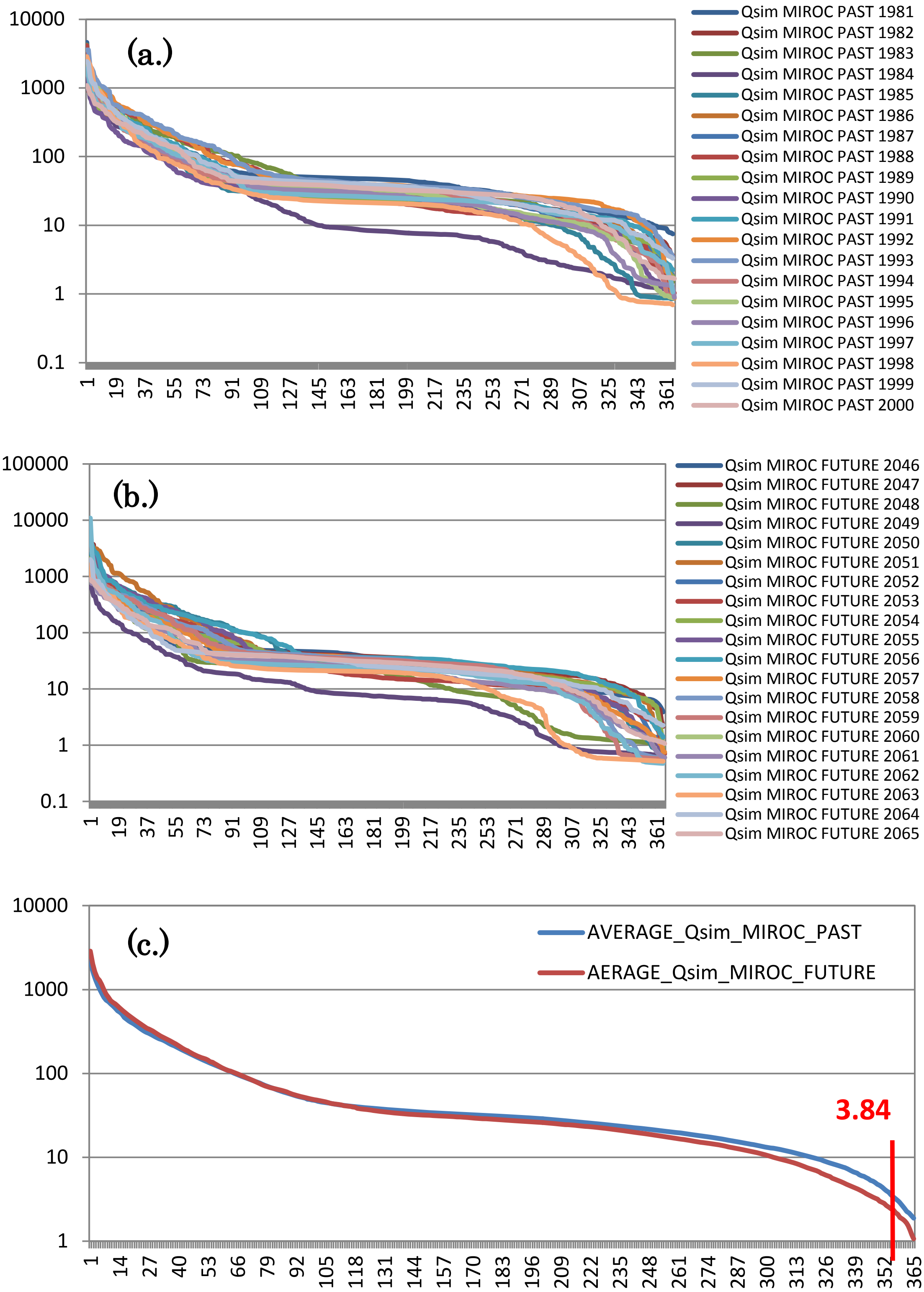


Figure 4.4-4. Discharge for the **a.)** past and **b.)** future 20 years of MIROC and, **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=3.84 m^3/s for San Isidro, Pampanga River Basin.

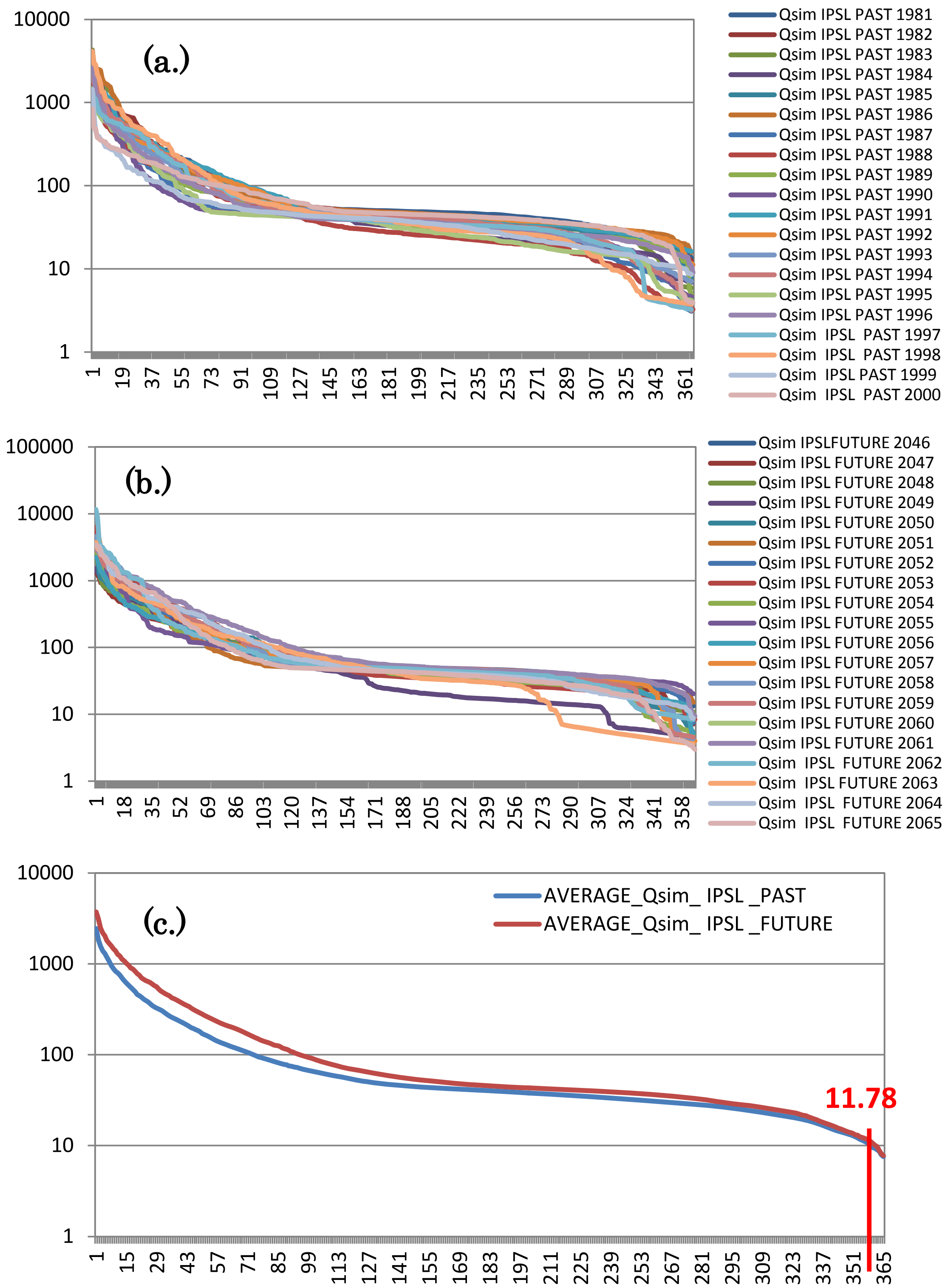


Figure 4.4-5. Discharge for the **a.)** past and **b.)** future 20 years of IPSL and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355^{th} day rank=11.78 m^3/s for San Isidro, Pampanga River Basin.

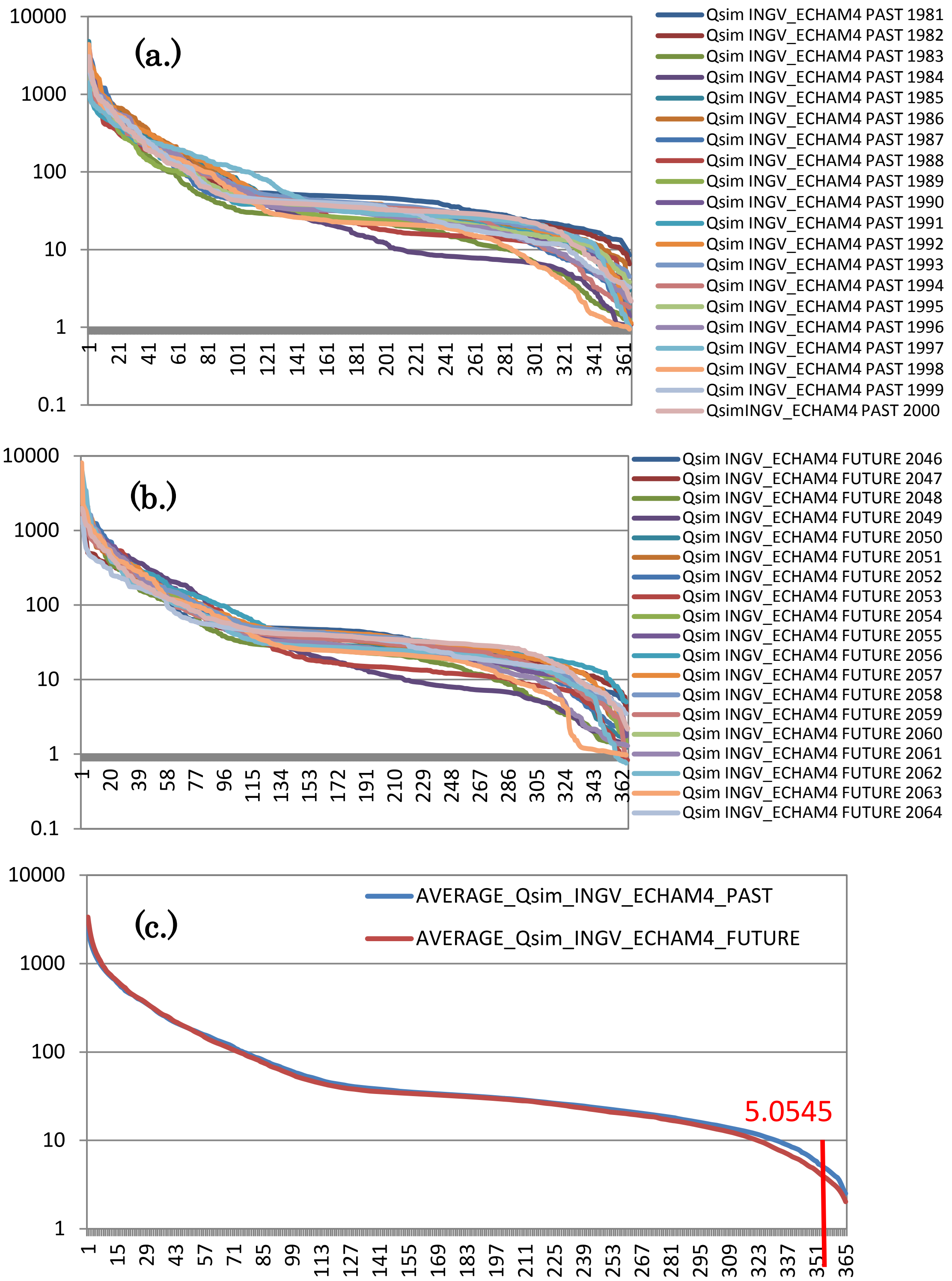


Figure 4.4-6. Discharge for the **a.)** past and **b.)** future 20 years of INGV and **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=5.05m^3/s for San Isidro, Pampanga River Basin.

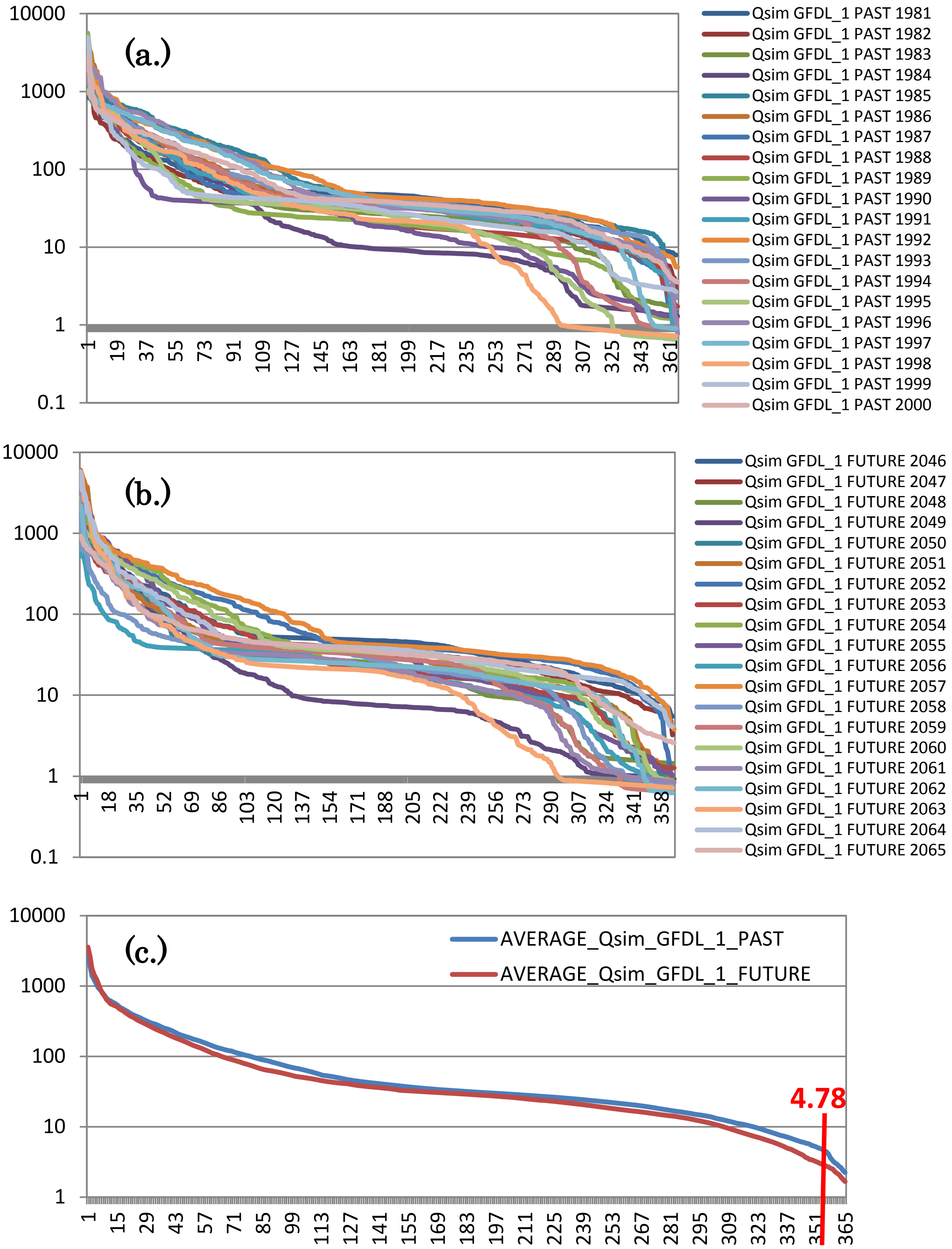


Figure 4.4-7. Discharge for the **a.)** past and **b.)** future 20 years of GFDL_1 **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=4.78m^3/s for San Isidro, Pampanga River Basin.

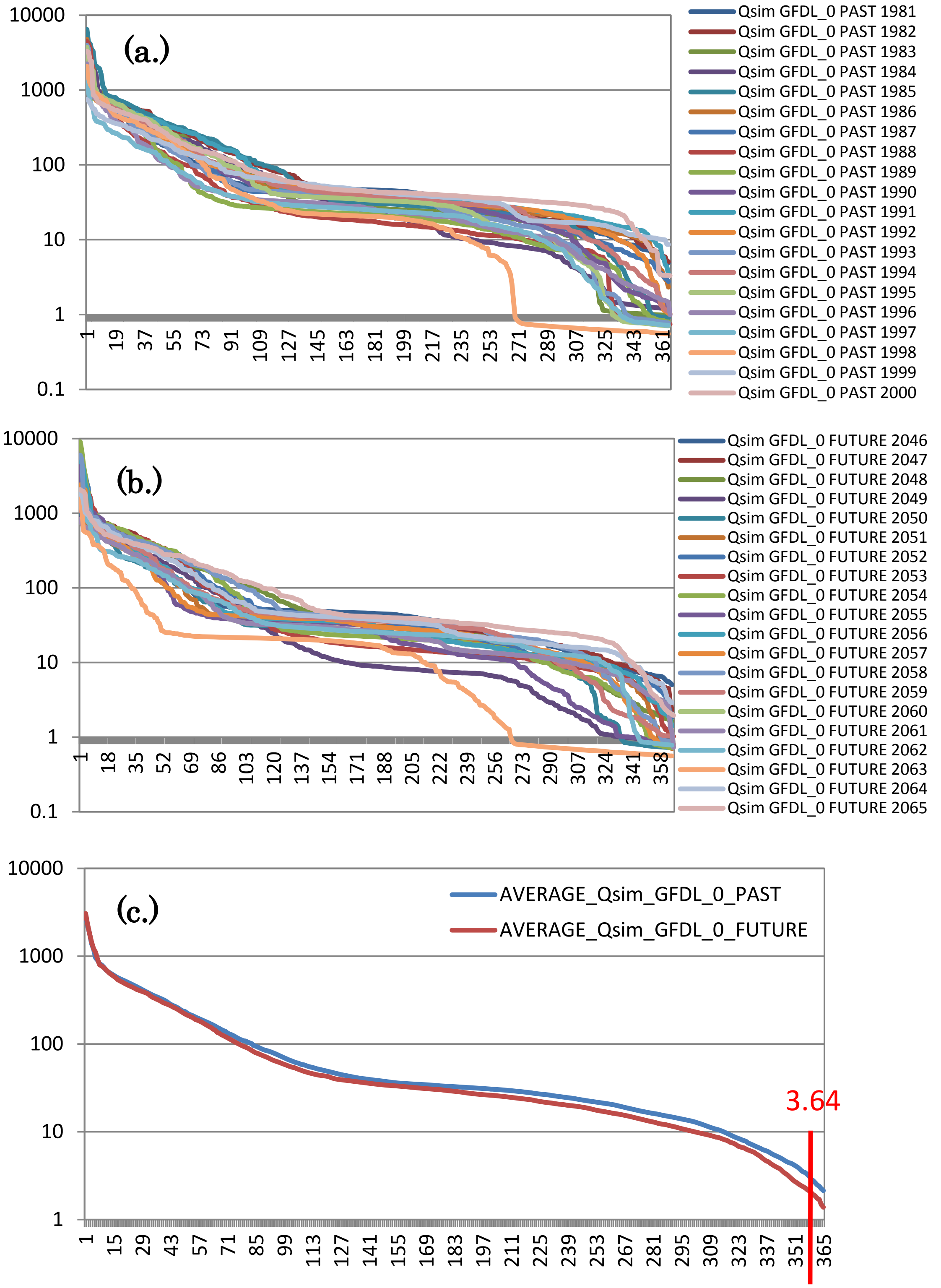


Figure 4.4-8. Discharge for the **a.)** past and **b.)** future 20 years of GFDL_0 **c.)** average of the same rank discharge for past (blue) and future (red) with past drought discharge at 355th day rank=3.64 m^3/s for San Isidro, Pampanga River Basin.

Table 4.4-1. Summary of flooding and drought trends from GCMs in San Isidro gauge, Pampanga River Basin

GCM Model	Flooding trends 10th percentile average Peak Flow (m³/s)		Drought Discharge (m³/s) (average 355th rank)		# of days/year that baseflow < past drought discharge (average of 355th rank)		Upper Limit of Drought Discharge (m³/s) 2nd lowest value* of 355th rank		# of days/year that baseflow < past drought discharge (2nd lowest value* of 355th rank)		Longest # of days (for each year below average drought discharge)		Change in SA (%)		
	Past	Future	Past	Future	Past	Future	Past	Future	Past	Future	Past	Future	ED	SD	MD
MIROC	2815.88	4280.53	3.84	2.529	22	34	0.899	0.58	3	9	93	106	-50	-75	-77
IPSL	3046.52	4698.92	11.78	12.547	19	19	3.791	4.209	2	1	54	87	--	33	0
INGV	3105.22	4061.48	5.05	3.96	18	22	1.528	1.451	3	5	54	57	--	-100	18
GFDL_1	3257.88	4609.88	4.78	2.93	30	43	0.749	0.665	2	2.95	96	111	100	0	37
GFDL_0	3759.39	4319.42	3.64	2.43	29	34	0.746	0.695	5	6	100	124	--	33	-13
CSIRO	2216.33	5955.37	12.66	9.948	21	35	2.763	1.905	2	7	57	79	--	--	62

Red=drier in future; more frequent below drought discharge

Blue=wetter in future; less frequently below drought discharge

ED=Extremely Dry condition SD=Severely Dry condition MD=Moderately Dry condition

*There are 20 values from the 355th rank of past 20 years and future 20 years. The 2nd lowest value for past and 2nd lowest value for future is used as upper limit of drought discharge and compared.

4.4.3 Longer Duration Droughts-Using SA

Similar to Angat river basin, results for the downstream discharge gauge projections of SA in the near future indicate a large uncertainty between models (**Figure 4.4-9** and last 3 columns of **Table 4.4-1**). Basin-scale average discharge for the entire Pampanga river basin showed that only miroc model increased in all SA categories while the rest showed different degrees of increase and decrease in the categories. The only difference is that, when compared with Angat simulations where future projections increased in moderately dry conditions only, for Pampanga river basin, severely dry conditions and extremely dry conditions are also projected in the near future (for 3 of the 6 models). Hence careful consideration of these (although not very frequent) extreme events in the future should be considered for basin wide water resources planning.

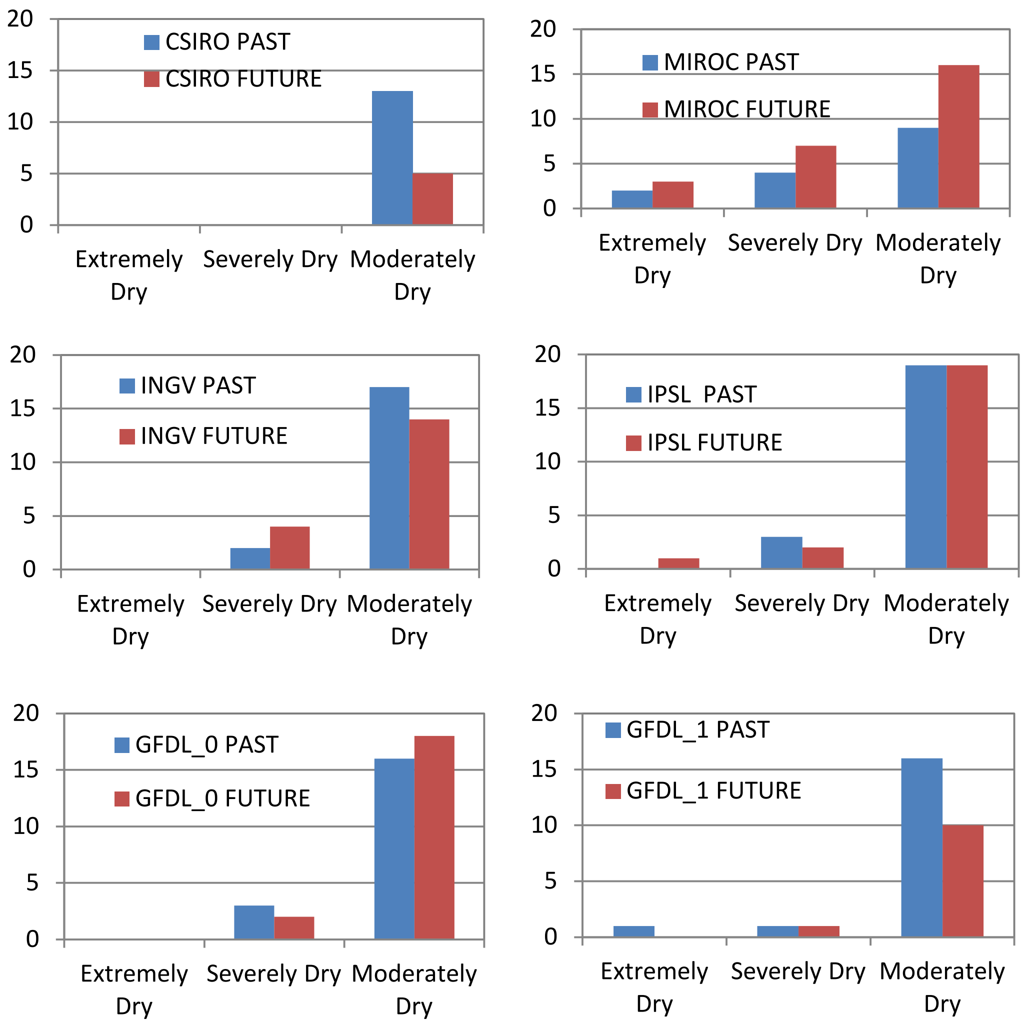


Figure 4.4-9. SA indices for the 6 selected GCM models for Hydrological drought in San Isidro gauge,Pampanga River Basin.

CHAPTER 5 Examination of the Optimized Operation of Water-Use Facilities

5.1 Recent Progress in Quantitative Precipitation Forecast (QPF)

Heavy precipitation events are very likely to continue and become more frequent as a result of global warming in the targeted river basins of this study, while there is still a large uncertainty as shown in **Chapter 3**. According to the IPCC Fourth Assessment Report [2007], the frequency of flood events has increased over most land areas, which is consistent with increases in land surface temperature. This is particularly evident in humid regions affected by tropical cyclones, such as Southeast Asia. These typhoons often bring heavy rainfall, but can cause severe flooding. A system is needed to reduce flood damage due to heavy rainfall and to make effective use of water.

Flood peaks can be reduced and water can be stored effectively by appropriate dam operation. The application of pre-established rule curves is limited during extreme flood events [Chang and Chang, 2001]. Optimal release systems using hydrological models to assist dam operators have been reviewed [e.g., Yeh, 1985; Labadie, 2004]. It is noted that because of the increase in computational power and real-time data availability, simulation approaches have become feasible and attractive [e.g., Wurbs, 1993]. Some of these studies focused on the optimization of operating rules for multi-reservoir systems taking advantage of real-coded genetic algorithms [e.g., Oliveira and Loucks, 1997; Chen, 2003; Chan, 2008]. Works 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]. A customized geographical information system to support dam release decisions in Korea [Shim et al., 2002]. Studies in Taiwan targeted real-time forecasting for flood control in Taiwan [e.g., Hsu and Wei, 2007; Chang and Chang, 2009, Wei and Hsu, 2009].

The accuracy of weather forecasting at the basin scale has improved in the last few years 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 [e.g., Golding, 2000; Krzysztofowicz et al., 2004; Honda et al., 2005]. Since precipitation is the main input data for hydrological models, the accuracy of 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 quantitative precipitation forecast (QPF), for the sake of appropriate dam operation. It suggests that this ensemble method might be also applicable into optimization of dam operation for reducing flood peaks and making maximum use of water. In this paper, a weighting module is proposed to account for the location, intensity and extension of the error. In this fashion, not only a missing precipitation pattern within contributing areas to dams, but also information from the surroundings can be considered in the system. The forecast error 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 a distributed biosphere hydrological model producing an ensemble stream flow. Using a threshold flow at the control point downstream, it is decided whether a particular member requires special dam operation. If so, a-priori independent dam release is activated considering the capability of flood attenuation with each reservoir. In order to minimize floods at the control point and maximize reservoir storage, a combined objective function is set-up. 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. Similarly, the lower boundaries are the mean minus one standard deviation.

The system was applied to one of the most important river basins in Japan, the upper Tone reservoir system. The system's efficiency was evident in reducing the flood peaks downstream and replenish/increase the storage volumes. The results from three events indicate the system is feasible in real-life dam operation. Then, decision-making during heavy rainfall for flood management is expected to be done considering the dam release uncertainty output of the system.

5.2 A Preliminary Study on In-advance Dam Release and its Potential Benefits

The Philippine Atmospheric, Geophysical and Astronomical Services Agency (PAGASA) has already introduced a radar rainfall measurement system and a numerical weather prediction model for their operational use. By applying the method developed by Saavedra et al. (2010) to the data obtained by the systems, there is a possibility of dam operation optimization for reducing flood peaks downstream and increasing storage volumes of the Angat Dam Reservoir for effective water use.

Priority on water use or priority on flood control. Usually, these two pose a conflict during actual operation. Our goal is to solve the conflict. The framework of this study is on Climate Change Impact Assessment and Hydrological Simulation. This consists of 3 parts, The first part is the climate change impact assessment on rainfall and its impact on river discharge and hydro cycle and then we summarized that it is virtually certain from 6 GCM models that can express the regional climate characteristics and all the GCMs show the increase of extreme floods in the future with no exceptions. In case of drought, half of the model show clear drought tendency while another half reduce drought risk. It is about as likely as not that severe drought will occur more often. The last component is the examination of the optimization operation of water use facility. There is one very useful and important reservoir: Angat and now the Philippines is planning to begin Laiban Dam construction. How to make maximum use of these facilities for addressing flood risk reduction and drought risk reduction. There is the Angat dam, and at the end of this basin, Matictic gauge station is identified. The purpose of this study is to maximize water storage in the reservoir to supply water to metro Manila (MWSS), provide enough height for hydropower generation (NIA) and provide irrigation water to Bulacan residents. For these purposes, the water level of Angat reservoir should be as high as possible. To minimize the flood risk in the downstream area, we need to control the WL downstream below the critical level. How to realize these 2 objectives at the same time? This is the objective of the study in preparation for the projected severe increase of flood in the future and the possible drought damage in the future.

There are three (3) main goals of this study: 1.) To determine how much decrease of the flood downstream after dam operation optimization; 2.) To identify how much water is stored effectively for future water use; and, 3.) To determine how we can keep the dam safe during optimization.

5.3 Angat Dam Specifications

Angat dam is a concrete water reservoir embankment hydroelectric dam that supplies the water to Metropolitan Manila. It supplies up to about 97% of raw water requirements for Metro Manila through the MWSS and irrigates about 28,000 hectares of farmland in the provinces of Bulacan and Pampanga. This dam was constructed in November 1961 and the gate was opened in October 16, 1967. The total height of the dam is 131m with a total length of 568meters and base width of 550 meters. 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 powerhourse) with an installed capacity of 256,000kW.

Angat dam has a normal high water level of 210 meters according to PAGASA. It has three gates opening a total of 1.5meters to gradually release water that had accumulated due to incessant rains during typhoons.

For the Angat dam, the flood season is very important for supplying the water into Angat dam to provide enough water to the dam. However, if the maximum level is exceeded, it may cause flooding in the downstream area. How to reduce the flood risk and maximize water use for the succeeding year. This is the table we received from NPC. The normal high water level is 212m above sea level however, this reservoir was operated at a maximum water level of 214m for 2011. The maximum is 219m but maximum permissible water level can reach as high as 217m. Above

208m dam operation begins, below this level, water is stored. Downstream critical water level is at 33.3m above mean sea level.

5.3.1. Operational Water Levels in a Multi-Purpose Dam or Reservoir

The main function of a dam is to produce a conducive downstream environment with specific characteristics. Usually, direct users of the upstream reservoir (fisheries, transport, recreation, etc.) are usually given second priority. Their interests may be sacrificed in the event of a shortage or surplus of affluent water in favor of maintaining the required discharge for downstream users. If a flood larger than the normal storage capacity of a multipurpose reservoir is expected, or dam discharge capability is impaired, the volume of the reservoir must be reduced considerably to accommodate the anticipated flood. This results to large fluctuations in reservoir water levels.

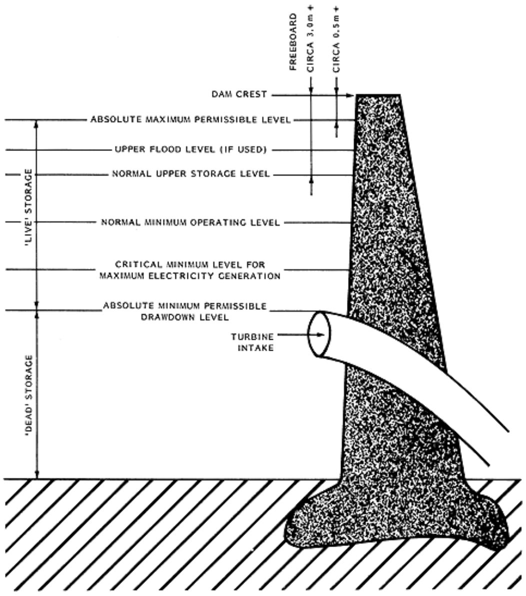


Figure5.3-1. Schematic diagram of various operational water levels for a hypothetical multipurpose dam/reservoir. (Source: http://www.fao.org/docrep/005/AC675E/AC675E04.htm)

The schematic diagram of various operational water levels for a typical multipurpose dam is given in **Figure 5.3-1**. Crest elevation is the principal design parameter determining the range of possible functions of a dam at a particular dam site. For most storage and control functions, crest elevation (freeboard = 3.0 m or more) is set to provide a certain impounded reservoir water volume. To reduce construction costs, the minimum crest height capable of performing the desired functions within a suitable safety margin is usually selected. Dams for hydroelectric power plants additionally need to provide hydraulic head. Hydraulic head is the vertical distance between reservoir water surface elevation and tailwater discharge elevation to the river downstream. This "drop" produces the hydraulic working pressure across the turbine blades which are situated at an optimum intermediate elevation. Increasing the reservoir water level (as a result of decreasing the crest elevation) increases the head to the turbine and in turn the potential electrical output of the power plant. Crest elevation will usually be maximized within the upper limits imposed by site geomorphology, economics and other factors. Both turbine efficiency and absolute power output would drop significantly if the hydraulic head is allowed to decrease. Thus, in theory, maximum electricity production requires the maintenance of the maximum possible reservoir water level at all times. In multi-purpose reservoir, this conflicts with the flood control function since maintenance of a constant level would require at any point in time releasing volumes of water almost equivalent to those entering the reservoir. This amount is somewhat less than affluent inflow due to evaporation loss from the reservoir surface. There would in effect be no flood control downstream. Thus, flood control requires a drawdown. To overcome this problem, the design head of the turbine is set at a lower reservoir water level elevation than that which will be maintained in practice, and flow to the turbines is controlled by valves. However, if reservoir water level is drawn down low enough to require fully opening these valves, any further drop will result in loss of electrical output.

5.3.2 Angat Dam Rule Curve

In the case of Angat dam, plots of historical water levels are given in Figure **5.3-2** below. Note that for the case of 2004, the water level dropped to a low of about 168m during the dry season and drastically spiked up to about 217m in November. These below and above normal reservoir elevation fluctuations need to be optimized to avoid possible damage as a result of drought or floods downstream.

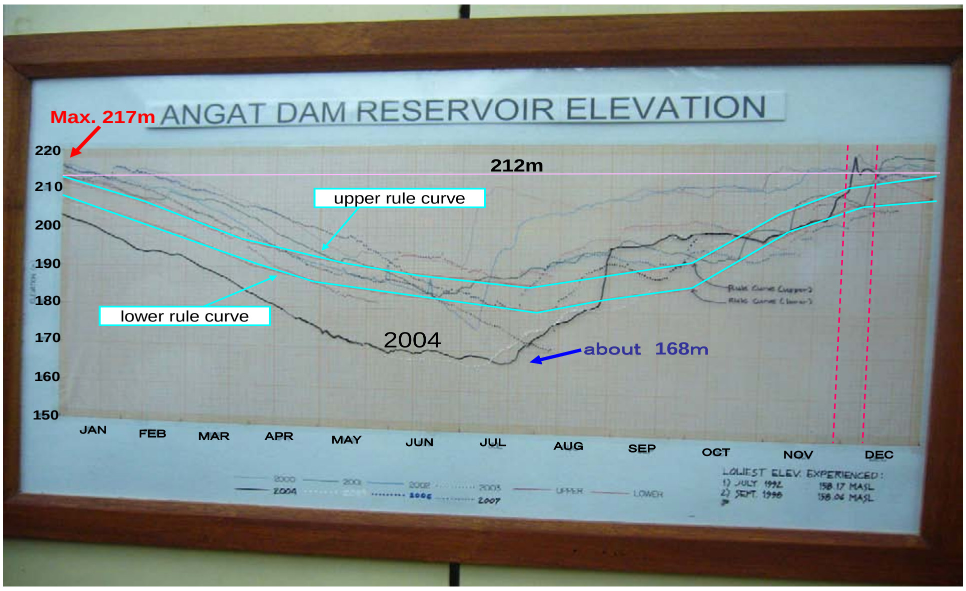


Figure 5.3-2. Rule Curve in Angat Dam.

For the hydrological simulations of this study, the following V-H curve (**Figure 5.3-3**) is considered for dam operation of Angat. This considers the minimum water level of 160m and the maximum water level at 219m.

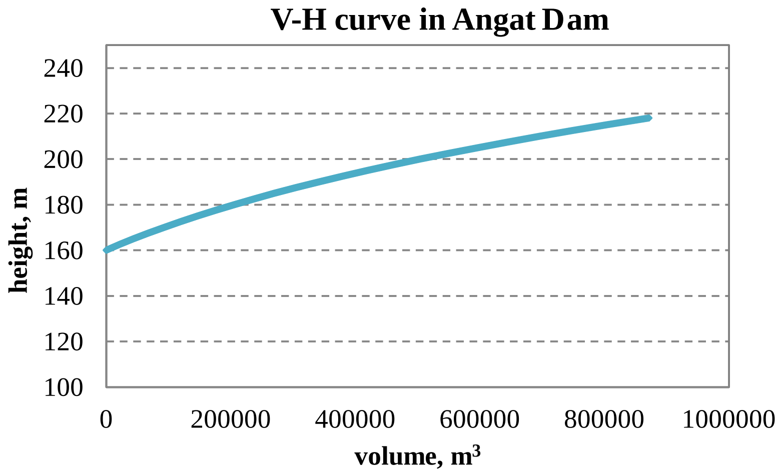


Figure 5.3-3. V-H curve in Angat Dam.

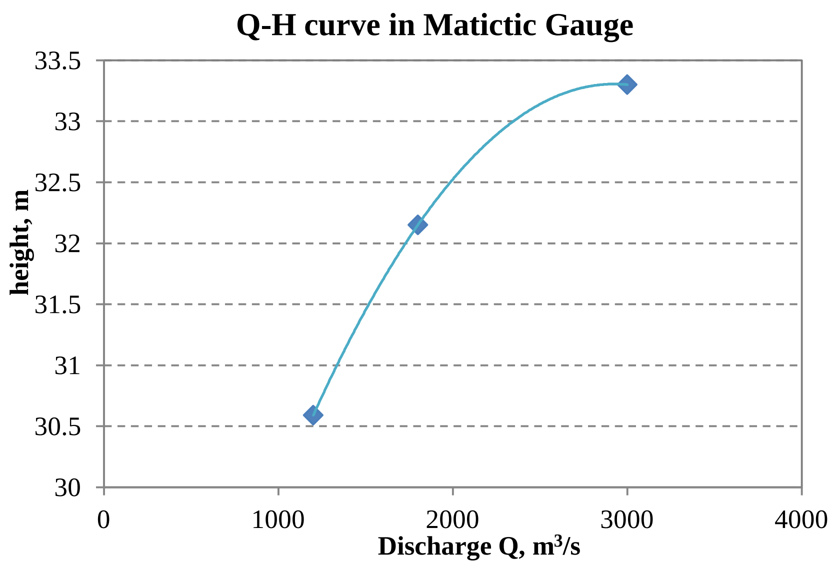
5.3.3 Upstream Water Storage Limitations in Angat Reservoir

The current limitations of Angat operations are given in **Table 5.3-1**. Angat has a drainage area of 568km^2 with a surface are at normal high water level (NHWL) of 23km^2. The lowest river elevation at the dam site is 92.5m above mean sea level (amsl). The normal high water level is set at 212m however, for the year 2011 in our case studies; this has reached up to more than 214m hence the maximum normal high water level is set at 214m. The design flood water level is set at 219m and the low water level at 180m. The lowest flow regulation level is at 208m below which operation is storing water in the reservoir, above which, dam operation begins.

Table 5.3-1. Current Angat Reservoir Specifications: Upstream

Drainage Area	568 km^2
Surface Area at NHWL	23km^2
Lowest river elevation at dam site	92.5m amsl
Normal high water level	212m amsl/214m amsl
Design flood water level	219m amsl
Low water level	180m amsl
Lowest flow regulation level	208m amsl

5.3.4 Downstream Flood Control Limitations



Q,m³/s	H,m
1200	30.59
1800	32.15
3000	33.3

Figure 5.3-4. Q-H Curve at Matictic gauge downstream.

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 33.3 m. Corresponding river discharges are also provided for these levels: 1200m^3/s, 1800m^3/s and 3000m^3/s. For the hydrological simulations, the Q-h curve given in **Figure 5.3-4** and **Table 5.3-2** are used with the maximum water level at 33.3m.

Table 5.3-2. Assessment of flow and water level at Matictic gauging station.

Alert: 1200cms	30.59m amsl
Alert:1800cms	32.15m amsl
Critical: 3000cms	33.30m amsl

The outflow from Angat Dam are given in **Table 5.3-3**. Note that it only takes 2.5 hours for flood to reach Matictic water level station. Bustos dam takes 5 hours and 40 minutes and the Bridge in Plaridel takes 8 hours and 20 minutes. 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. The schematic diagram of the current releases of Angat dam are given in **Figure 5.3-5**.

Table 5.3-3. Flood wave propagation time from Angat dam.

Ipo dam 0 hr 0 min	Bustos dam 5 hr 40 min
Matictic WL station 2 hr 30 min	Bridge in Plaridel 8 hr 20 min

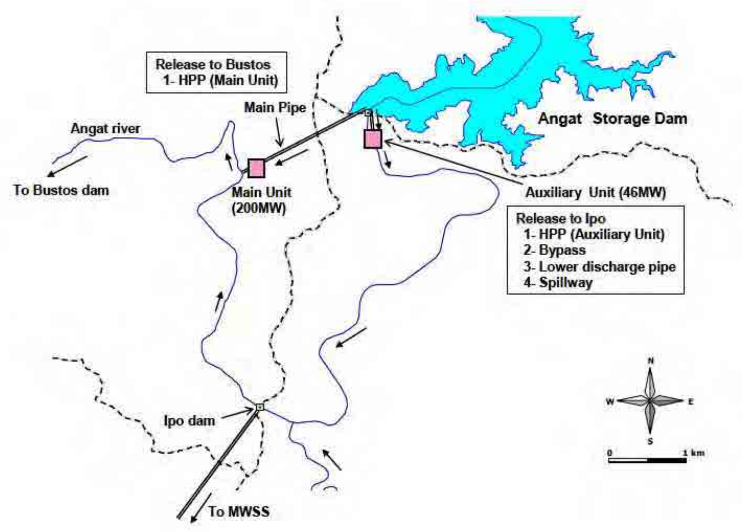


Figure 5.3-5. Current releases from Angat Dam to Ipo Dam and Bustos Dam.

5.4 Input Data Preparation

5.4.1 PAGASA WRF Forecast for Rainfall

In this study, rainfall forecast data from WRF assimilation by the Philippine Atmospheric Geophysical and Service Administration (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 to 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 assimilation covers 182 x 214 outer grids with nominal grid spacing of 12 km. The inner grid is 361 x 593 with a nominal grid spacing of 3 km. The model is run with 28 vertical levels. One-way nesting describes the currently-configured interaction between the inner and outer grids. In this type of interaction, the inner grid solution has no impact upon the outer grid. (**Figure 5.4-1**).

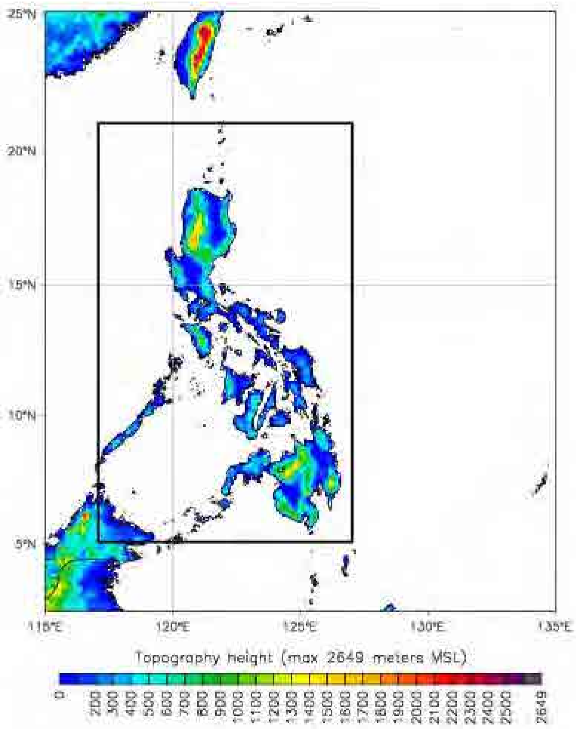


Figure 5.4-1. Dimensions of the forecasted WRF outputs from PAGASA.

This numerical weather prediction of PAGASA is compared with observed stations data for the case studies in 2011, only two out of the four rain gauges were functioning.

Extreme Rainfall Events in 2011

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 24-28), 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/persons although it came only second (with 85 persons) to Sendong (with 1,257 persons) in terms of the number of casualties.

Currently, six (6) extreme events passing thru Angat river basin are being archived in DIAS. These are for SW Monsoon (Habagat) 2012 and Gener 2012. Typhoon Pedring (September 24-28, Quiel in 2011 (Sept. 29, 2011-October 1, 2011); Sendong (December 15, 2011 to December 18, 2011); Ramon (October 10, 2011 to October 14, 2011); and Gener (July 29, 2012 to August 2, 2012). Unfortunately the forecast datasets for SW Monsoon, Sendong and Gener were incomplete hence, only Pedring, Quiel and Ramon are considered in the sample case studies.

Typhoon Pedring (Typhoon Nesat) was selected for several cases in this study 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, IV-B, V, 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)

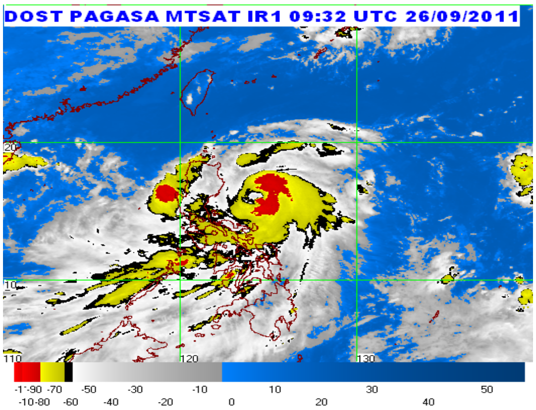


Figure 5.4-2. Typhoon Pedring affecting Luzon and Visayas. (Source: PAGASA)

Typhoon Quiel (official name Nalgae) is the second typhoon within the week to hit Northern Luzon. 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 area triggered landslides and flooding.

Figure 5.4-3. Typhoon Quiel affecting Luzon. (Source: PAGASA)

The other case considered in this study is during Tropical Depression Ramon. The estimated rainfall amount for Tropical depression Ramon was 5 to 25mm/hour (moderate to heavy) with the 300km diameter. However, the soil layers during this time are also saturated and the water levels in the dams are above the average. Hence flooding in downstream

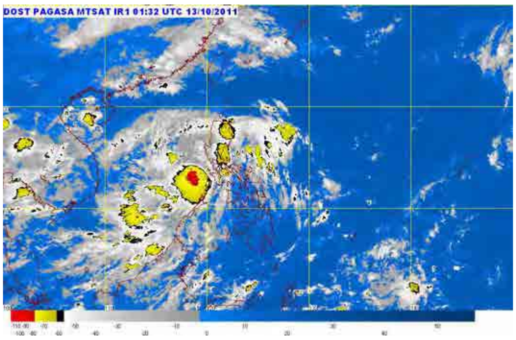


Figure 5.4-4. Tropical Depression Ramon affecting Luzon. (Source: PAGASA)

5.4.2 Ensemble Rainfall Generation

For each extreme event, 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 (forecast prediction error). The same procedure is done for the succeeding time steps of the forecast prediction. **Figure 5.4-5** shows that forecast data from previous time steps (e.g. 18:00 to 24:00 time slice; in the case of 6 hourly updating, there are 4 datasets to compare with observed rainfall) are evaluated for the errors. These errors are applied to the next prediction period (0:00 to 6:00; 6:00 to 12:00; 12:00 to 18:00 and so on). This error can be 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. In the case of Angat, 10 ensemble members were formulated to account for the error range between observed and forecast data. This ensemble rainfall is incorporated into the hydrological model for flood prediction.

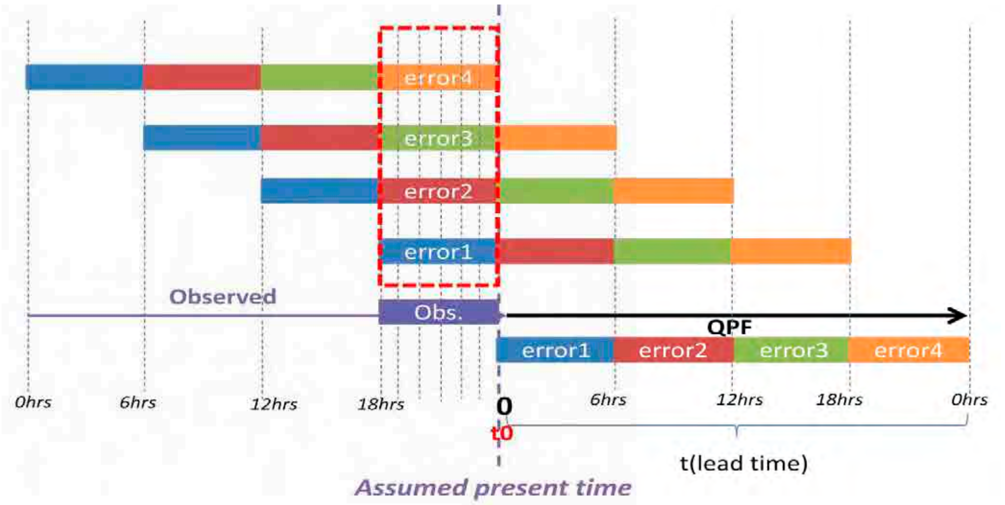


Figure 5.4-5. Error evaluation used 6 hours past information to create the QPF members.

5.4.3 Real-Time Data Management System

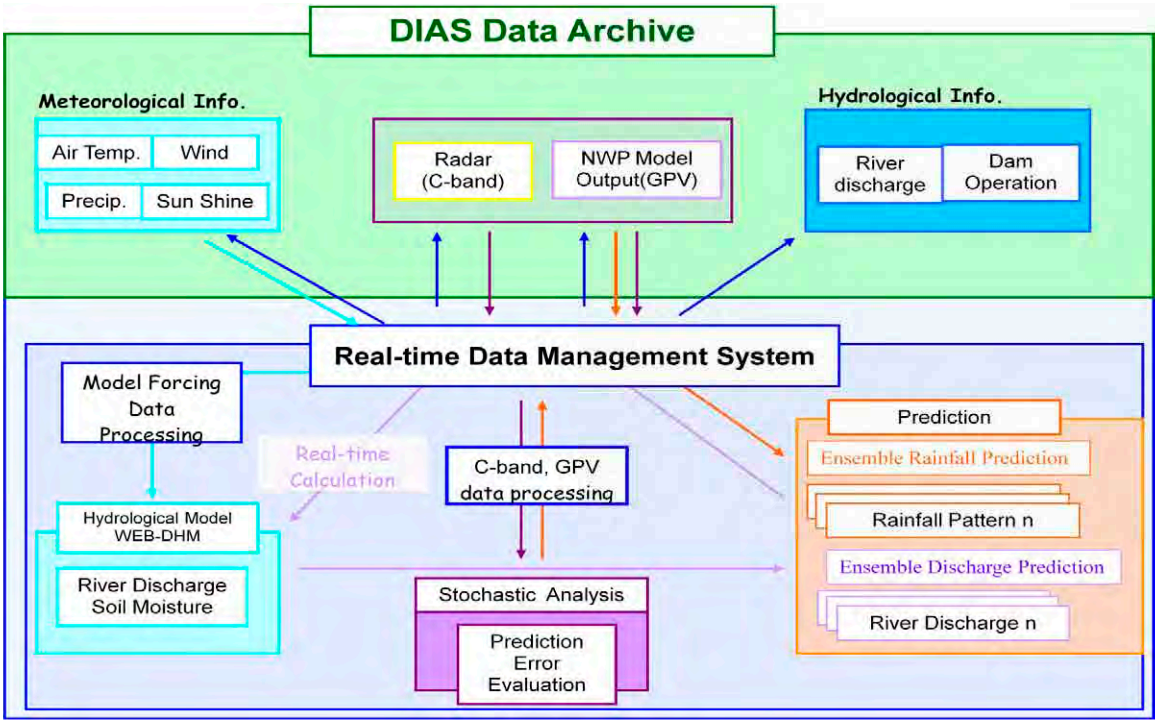


Figure 5.4-6. DIAS Real-time Data Management System.

In Japan, a real-time management system (**Figure 5.4-6**) was developed and currently managed in the Data Integration and Analysis System (DIAS) of the University of Tokyo by using meteorological data in real-time basis incorporated into the same hydrological model (WEB-DHM) to simulate river discharge and soil moisture in a distributed way for every time step in real-time basis to optimize dam operation in Tone River Basin.

Meteorological information and GPV data is provided by Japan Meteorological Agency (JMA), hydrological information comes from MLIT. Data availability and data sharing in real-time is very important between agencies.

5.5 Introduction to Dam Optimization

5.5.1 Offline Dam Operation Optimization

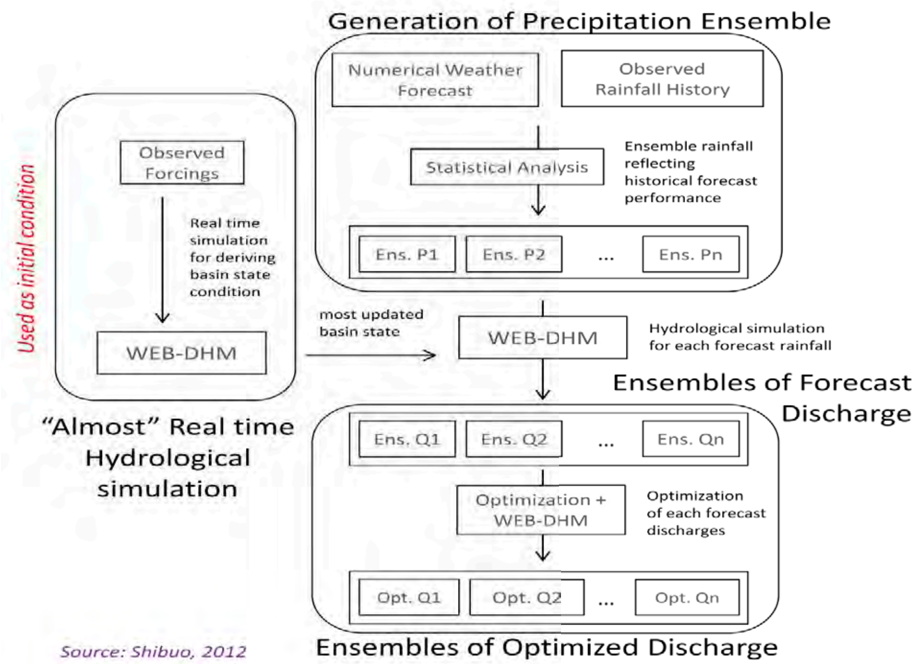


Figure 5.5-1. Overall framework of the offline dam operation optimization system.

The optimization scheme (**Figure 5.5-1**) developed for the case of the Philippines consists of 4 components:

1.) By using observed rain gauge data we can run hydrological model (WEB-DHM) to simulate basin-scale hydrological conditions (discharge, soil moisture, water levels)
2.) PAGASA's numerical weather prediction data accounting for error prediction can be introduced every 6 hours.

3.) The rain gauge data and numerical prediction data are merged and error was calculated. Ensembles were then produced.

4.) By applying the optimization scheme, the objective functions (maximize water use and minimize flood risk) are applied to each of the ensemble members.

5.6 Preliminary Dam Optimization Considering Water Storage and Flood (upstream case only)

As a preliminary check of this optimization study, the case of the extreme event when both typhoon Winnie and Typhoon Yoyong simultaneously ravaged the Philippines in November 28 to December 3, 2004 is analyzed for in-advance dam release (pre-release) and its benefits in a very simple case where a perfect prediction is assumed and same weights (α_1=0.5 and α_2=0.5) are applied to the cost functions, one for flood risk reduction and another for effective water use. This is expressed in the following equation:

$$\alpha_1 \times \sqrt{\frac{\sum_{i=1}^{N}\left(Q_{out}-1700\right)^2}{N}} + \alpha_2 \times \sqrt{\frac{\sum_{i=1}^{N}\left(H-217\right)^2}{N}} \qquad \text{(eq.20)}$$

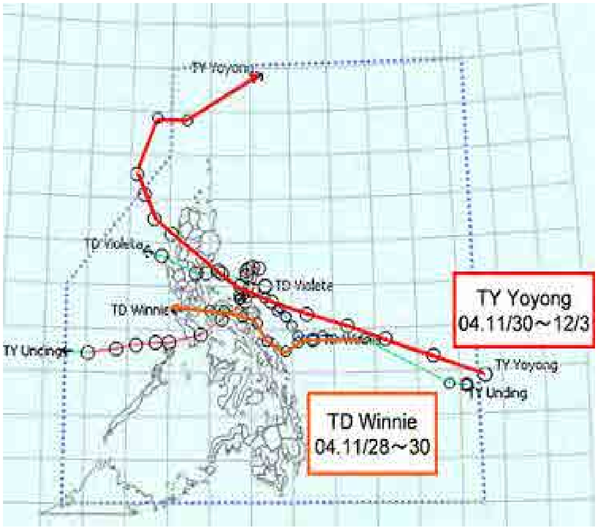


Figure 5.6-1. Typhoon Winnie and Typhoon Yoyong tracks for the preliminary study.

Figure 5.6-2 and 5.6-3 are simulation results of a big flood case from 27 Nov. to 04 Dec., 2004, assuming larger capacity of flood control with the lower initial reservoir water level, 212m, and less with the higher, 217m, respectively. They show that appropriate in-advance dam release based on QPF with reasonable accuracy can achieve flood risk reduction and effective water use both.

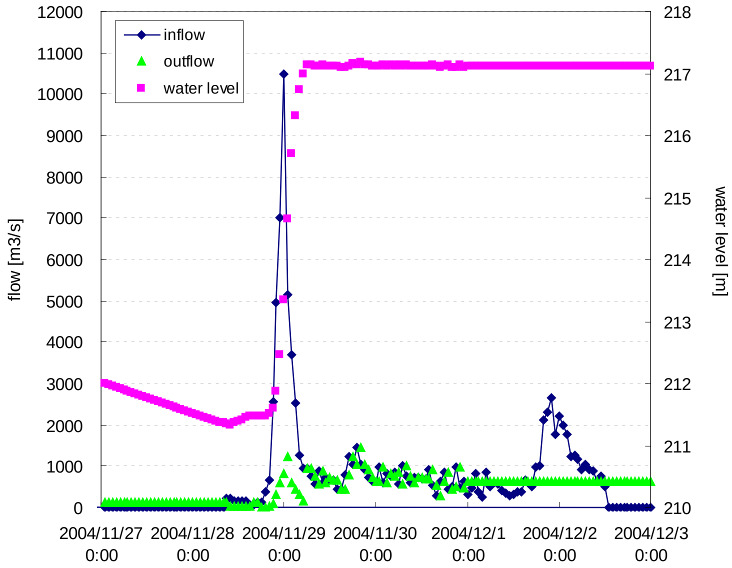


Figure 5.6-2. Angat Dam reservoir optimization. Case 1: initial water level at 212m; (a = 0.118 ; prerelease (Q_{pre}) =120.9m^3/s and maximum WL = 217.179m)

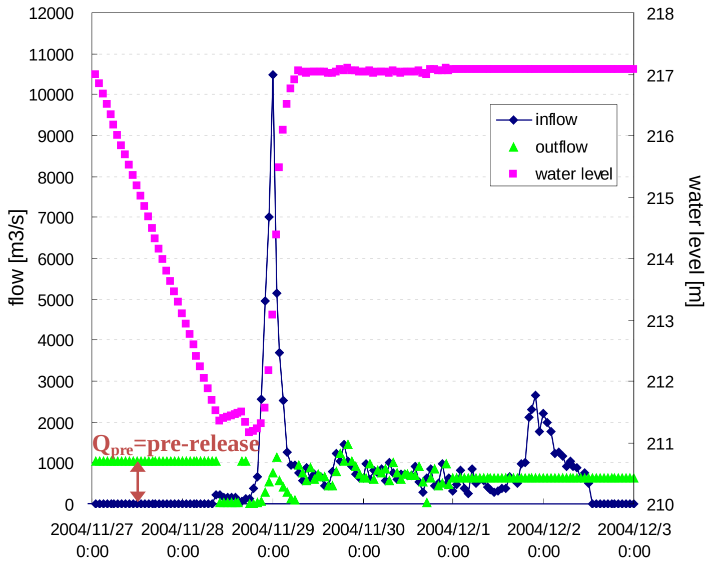


Figure 5.6-3. Angat Dam reservoir optimization. Case 2: initial water level at 217m; (a = 0.109; prerelease (Q_{pre}) =1049.6m^3/s; maximum WL = 217.091m)

5.7 Finalized Dam Operation Optimization System

From the first part of this report, extremely high discharge flows are expected to increase in the near future based on six selected GCM models. This verifies previous global studies that climate change in the Asian Summer Monsoon Regions is expected to increase in the near future (Kim and

Byun, 2009). IPCC predicts that heavy precipitation events will very likely become more frequent because of climate change (IPCC, 2007). In the Asian Summer Monsoon Areas, especially in the Philippines, the increasing number and intensity of typhoons making landfall has brought about severe flooding in low lying areas such as that in Metropolitan Manila. As a result of this, increasing severity of flood damage at the basin may also increase. Results on assessing the impacts of climate change in the first part of the study further support this increased risk. Increases in future flood peaks in Angat river basin are virtually certain (Jaranilla-Sanchez, et al., 2013). Hence both hardware (construction of reservoirs, levees and dams) and software (careful consideration on how to operate the dam more efficiently) should be considered to minimize the impacts of future floods.

5.7.1 The DRESS System

To respond to this risk and thereby reduce flood damage, the Dam Release Support System (DRESS) (**Figure 5.7-1**) was utilized to support flood management upstream using real-time observations and forecast data. One of the main issues with forecast information is the accuracy of rainfall predictions as the accuracy of the Quantitative Precipitation Forecasts (QPFs) are reflected in the simulated streamflow forecasts.

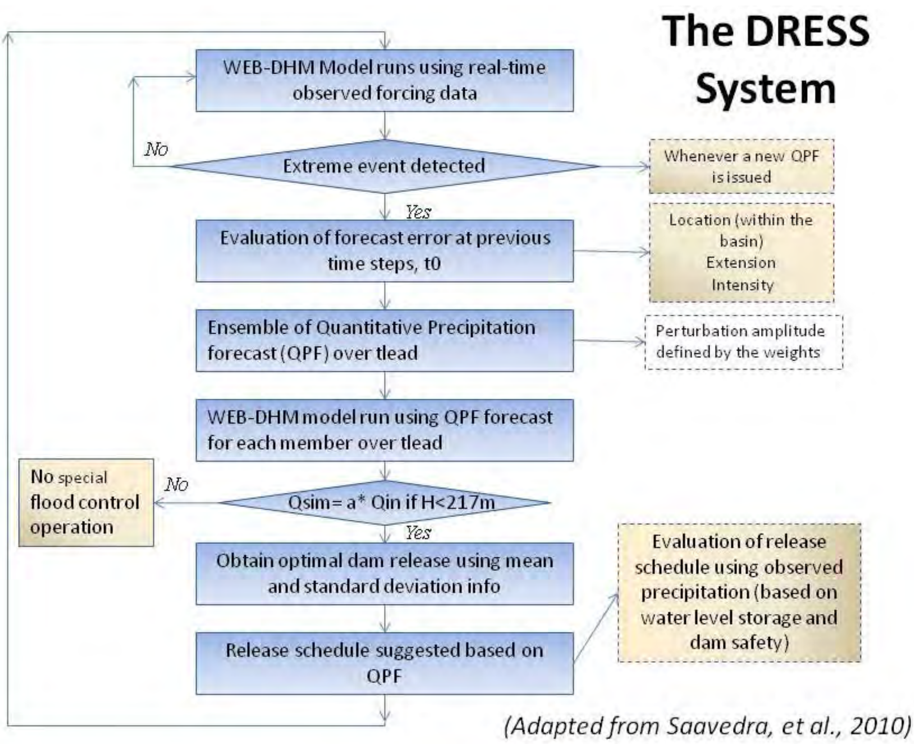


Figure 5.7-1. Framework on how the DRESS system was used for the case of Angat Dam.

This Study adapts the DRESS method developed by Saavedra Valeriano et al., (2011) to optimize dam operation. Firstly, WEB-DHM is run using observed real-time forcing data. If an extreme event is detected (such as the case of typhoon Pedring), the forecast data is evaluated using the error from the previous time step. The same time period is evaluated for error and compared with observed rainfall. A weight table is used to evaluate the error. The evaluation is based on three parameters: location (in this case since observed rainfall data is only available within the basin so error evaluation is done within the basin), intensity and extent. These are evaluated for each time step and corresponding ensemble members are created. For each time step, error evaluation is done in the same manner. The specific steps for the error evaluation and ensemble member generation are further described in Appendix 1 of this report.

For this study, 10 ensemble members were created to evaluate the forecasts for typhoon Pedring with a lead time of six (6) hours. Each ensemble member is run into the hydrological model and optimized for 24 hours. Initial dam status of the previous hour is used as initial condition of dam water level and dam volume. Currently, the dam optimization scheme was structured to run with one forecast issuance in each day. The forecast capabilities of PAGASA has been made operational from 2011-2012. Currently, three (3) extreme events passing thru Angat river basin awill be considered for the cases: Quiel 2011, Pedring 2011 and Ramon 2011.

5.7.2 Dam Operation Objective Functions for Water Storage and Flood (considering upstream and downstream)

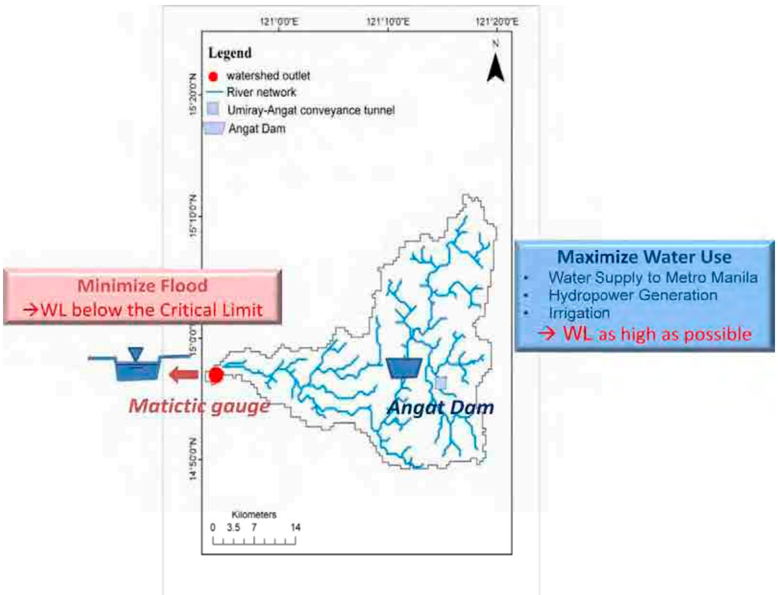


Figure 5.7-2. Objective function of dam optimization for Angat.

The preliminary case study used to check dam operation considered only upstream water level and outflow conditions. In this succeeding section, 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 hydropower generation (also the mandate of NIA). At the same time, to avoid the 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). **Figure 5.7-2** shows the 2 objective functions considered in the dam operation optimization system developed for Angat dam.

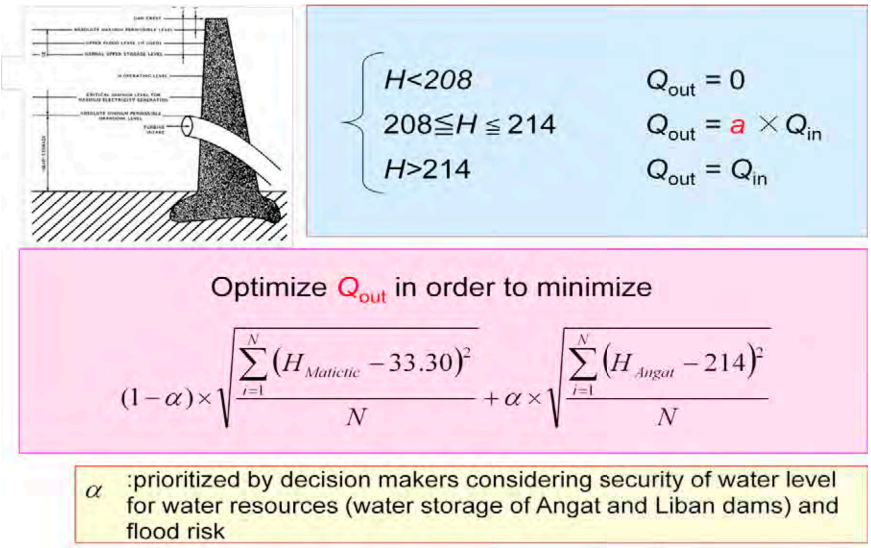


Figure 5.7-3 Optimization of Angat Dam operation.

Additionally, modifications from the preliminary study assumptions and equations are given in **Figure 5.7-3**. The objective function priority will be determined from the priority setting of decision makers for different extreme events. Hence it is possible for α and the height limits to vary for different extremes. Hence, different variations of priorities and height limits as well as water levels are considered in the succeeding cases. If additional future reservoirs and dams will be added in the future, the priority setting can be based on the existing conditions of the adjacent dams as well. A hypothetical case for Laiban dam is shown in the next section.

5.8 Possible Decision-Making issues: Laiban Dam Assumptions

Angat is a very important dam for Metro Manila. Now, the GoP is planning to construct Laiban Dam. In this section the main question to answer is: If in the future both dams will be made available, how to make maximum use of these facilities for addressing flood risk reduction and drought risk reduction? Hydrological simulations upstream of Kaliwa river basin to the future location of Laiban Dam is given in the lower portion of **Figure 5.8-1**. The design effective reservoir storage capacity of Laiban is given at 470MCM aimed at supplementing a daily discharge of 22m^3/s. The hypothetical drawdown curve is calculated based on varying initial conditions: half, one-third, two-thirds, at dead storage and at full capacity. For the 3 extreme events (**Figure 5.8-2** for daily rainfall and **Figure 5.8-3** for the corresponding inflows to Laiban dam): Pedring, Quiel and Ramon. The daily rainfall pattern during typhoon Pedring is shown in **Figure 5.8-2** with the more than 200 mm/day rainfall observed in Sept. 27. For the optimization during Pedring, focus will be given to the extreme event on this day. The daily rainfall of Quiel and Ramon are not as high as Pedring however, the initial water level prior to these events are already high.

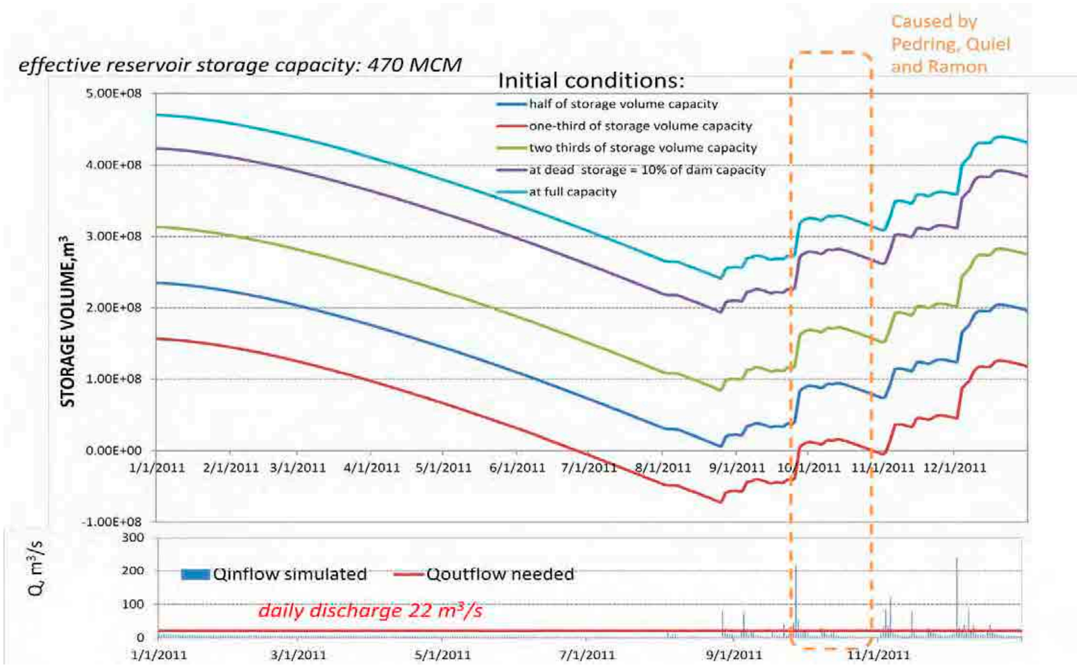


Figure 5.8-1. Laiban Dam hypothetical 2011 drawdown curve from various initial conditions.

If the water level in Laiban dam reservoir is high, then priority of the objective function on keeping the water level in Angat as close as possible to the limit can be reduced since Laiban can supplement some of the water requirements of the downstream stakeholders. However, if Laiban dam is almost empty, Angat dam optimization should prioritize keeping the water in the upstream as high as possible (store all the water in Angat). Such a complementary system can be implemented in the future when more structures will be constructed to for water use in Metro Manila.

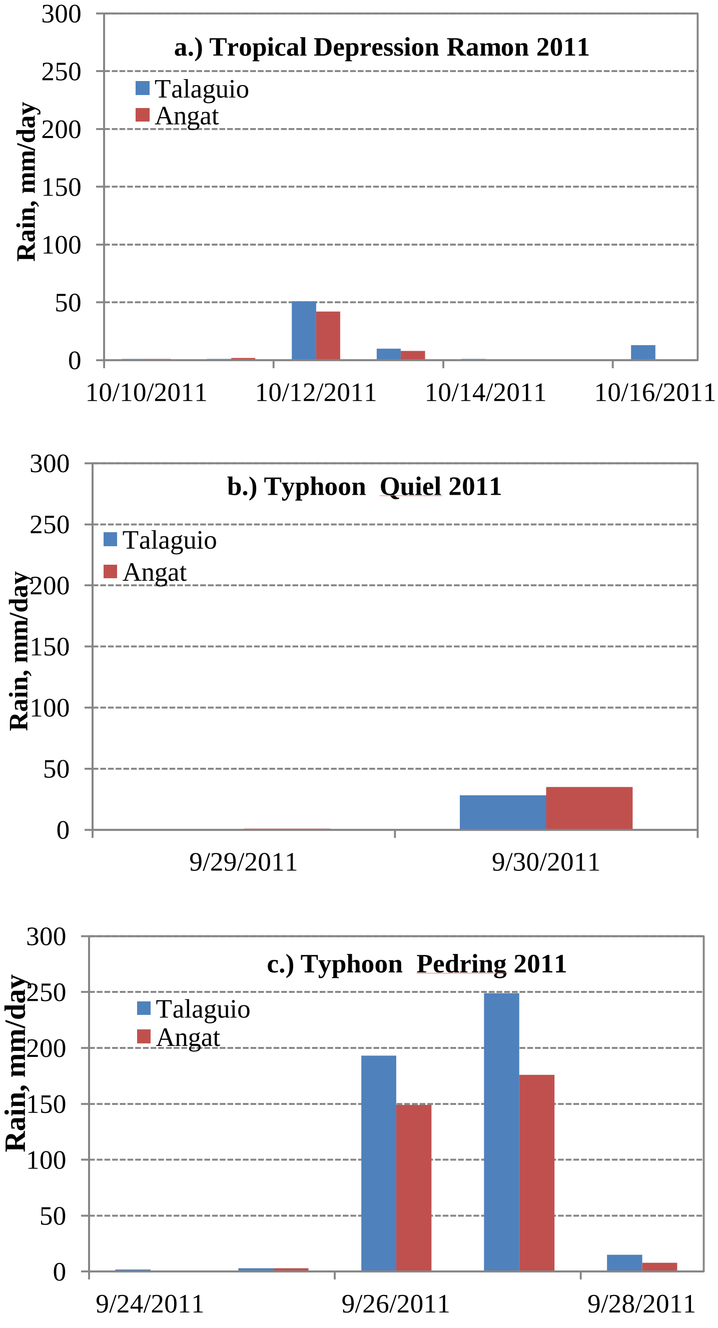


Figure 5.8-2. Daily Rainfall for the 3 Typhoons: **a.)** Ramon, **b.)** Quiel and **c.)** Pedring.

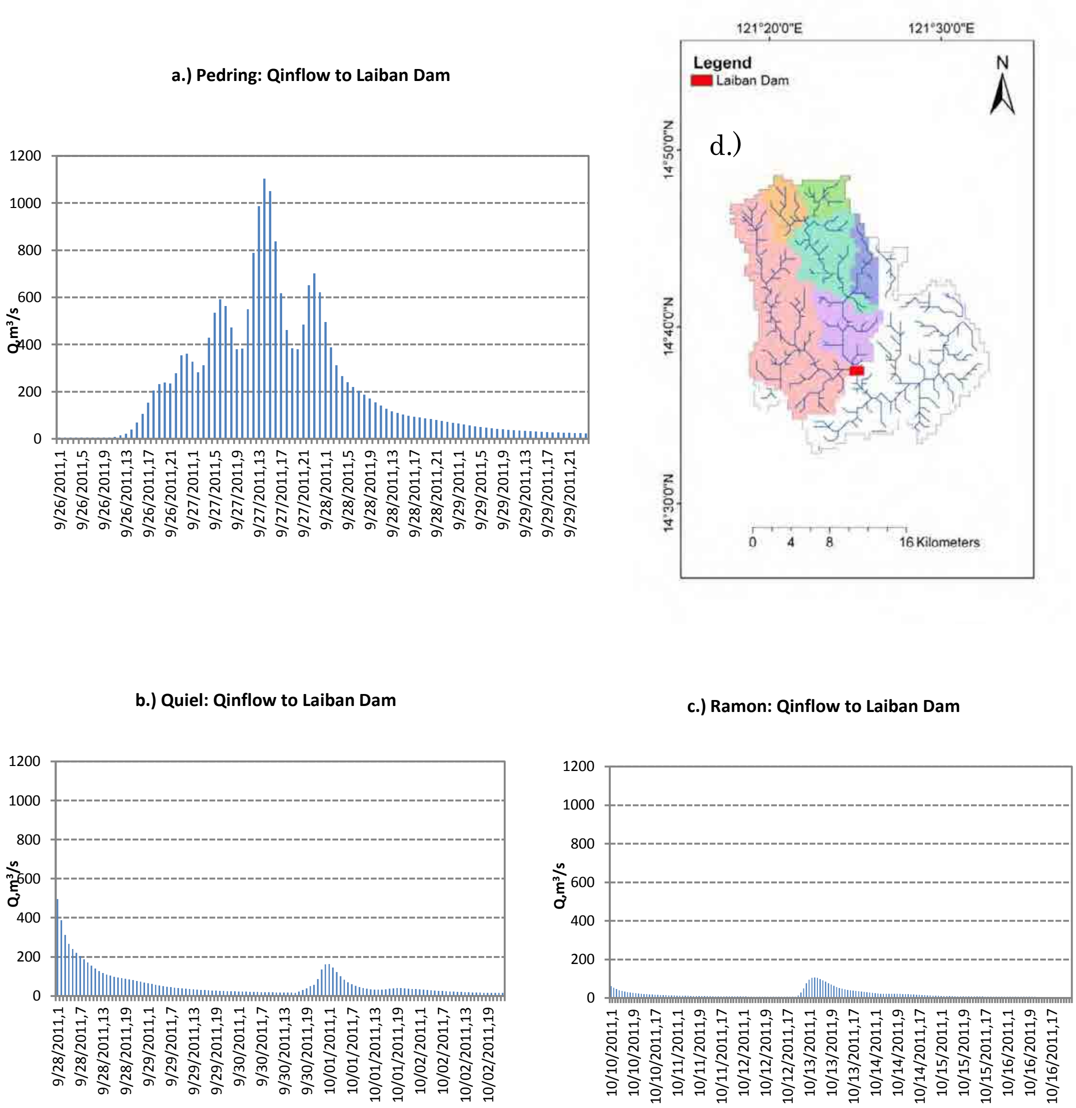


Figure 5.8-3. Inflows to Laiban Dam for a.) Pedring, b.) Quiel and c.) Ramon and d.) the hypothetical future location of Laiban dam in Kaliwa river basin hydrological simulation.

In sections **5.9** to **5.13** The following questions are attempted to be answered:

1. How can we maximize storage in the dam using optimization?
2. Can dam optimization work if initial water level is already very high?
3. What are the different effects of varying priorities on the flood and water storage?

4. If we have a more limited storage capacity of the dam, how will the dam optimization work as compared with if we have more storage available (as in the earlier cases)?
5. For the same typhoon, what if the initial condition is at a level where the water storage capacity of the dam is not enough to accommodate all the water?

The following cases are provided to attempt to illustrate answers to these questions.

Case 1: Typhoon Quiel at 214m water level limit with observed dam release and 50% priority on preventing flood and 50% priority on water storage.

Case 2: Tropical Depression Ramon at 214m water level limit with observed dam release and 50% priority on flood and 50% priority on water storage.

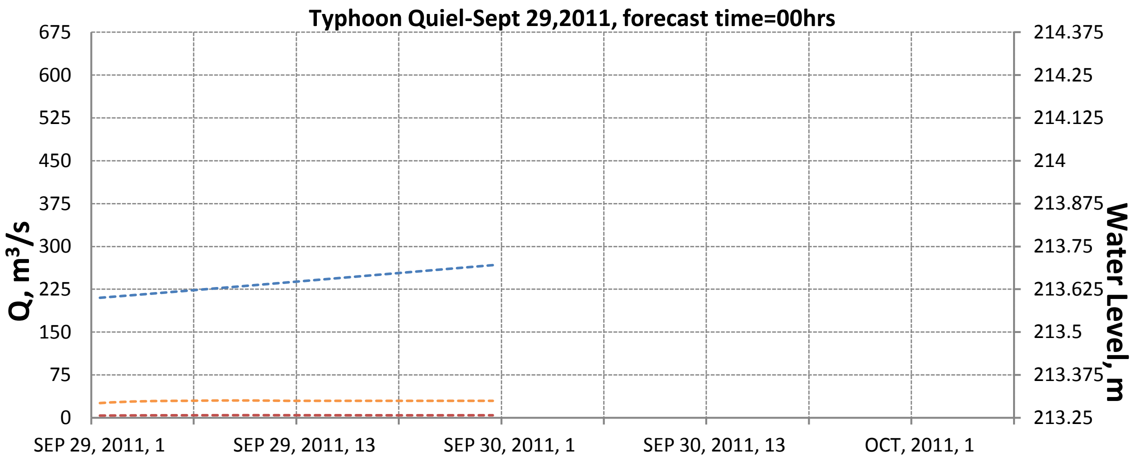
Case 3: Typhoon Pedring at 214m water level limit with observed dam release, with 0% priority on Flood and 100% priority on water storage; 20% -80%, 50%-50%.

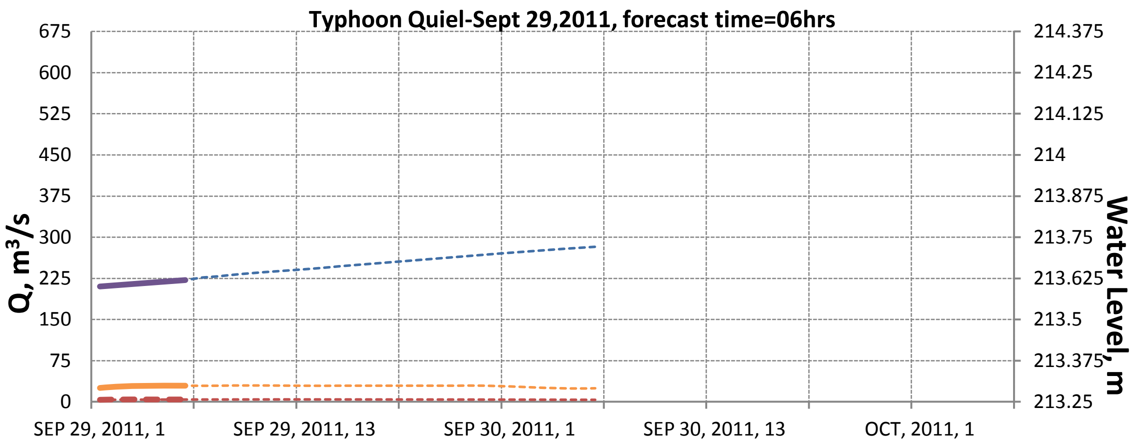
Case 4: Typhoon Pedring with a different initial water level at Sept. 26 (from 207m to 212m).

Case 5: Typhoon Pedring at 212m water level limit at 50%priority on flood-50% priority on water storage.

5.9 Case Study 1: Typhoon Quiel at 214m Water Level Limit with Observed Dam Release and 50% Priority on Preventing Flood and 50% Priority on Water Storage

Typhoon Quiel actually made landfall a week after Typhoon Pedring. However, it is presented here first to illustrate how dam optimization can maintain the high water level even if the initial water level is already near the maximum. **Figure 5.9-1** illustrates how the dam optimization behaves in each of the 6 hour time interval for discharge inflows, outflows and reservoir water level. On September 29, 2011, the observed water level at 213.6m (daily values by NIA) is used as initial condition. At 50% priority to keeping the water level as high as possible and 50% priority on keeping the downstream water level below 33.3m, some dam release can be afforded in the dam while maintaining water level below the 214m limit.





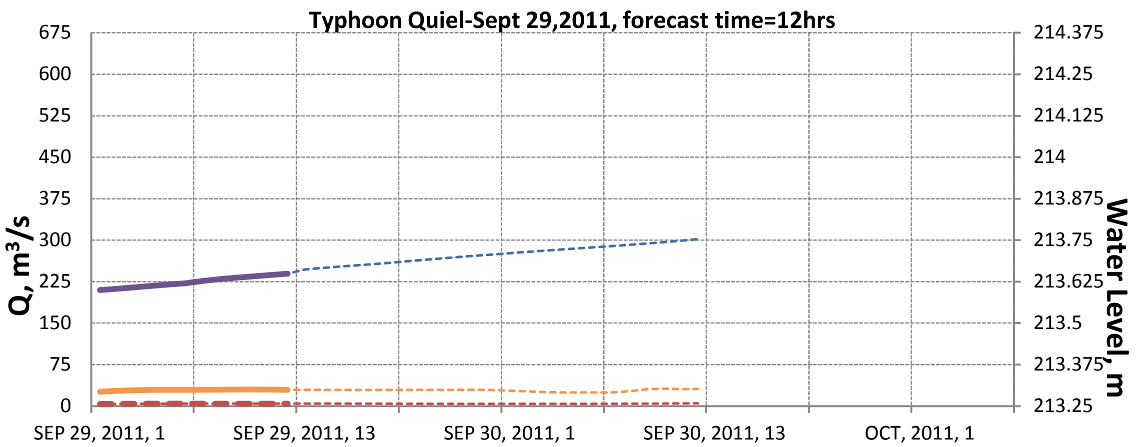


Figure 5.9-1. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for Typhoon Quiel with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps) (cont.)

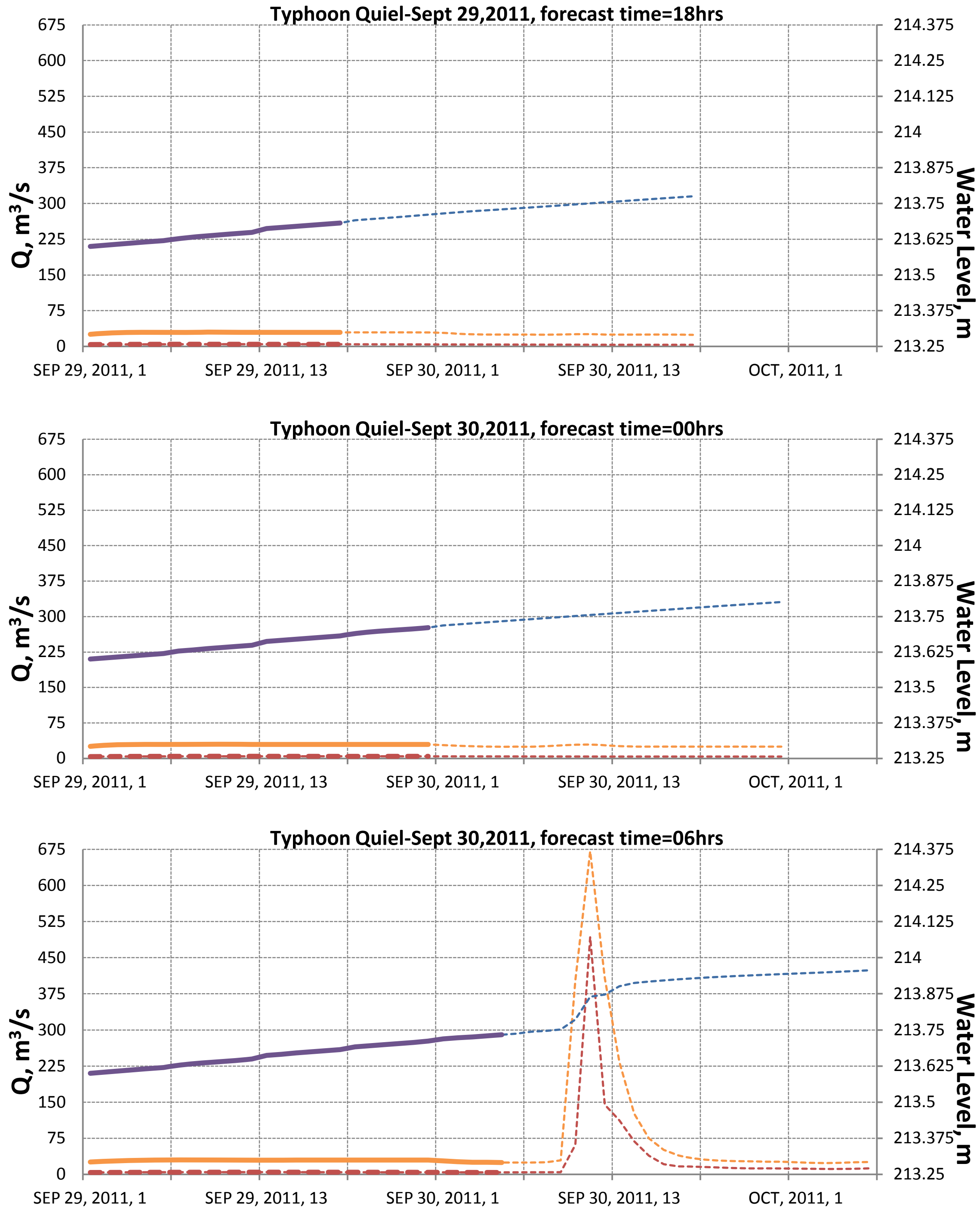
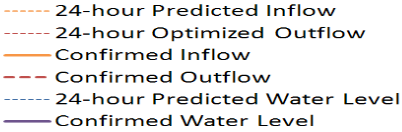


Figure 5.9-1. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for Typhoon Quiel with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps[see legend])



A summary of simulated inflow from observed rainfall versus predicted inflow from the average of the 10 ensemble members show there are some differences in the timing of the discharges from observed and forecasted rainfall. Additionally, that the average of the ensemble members has a peak discharge of 1.5 times higher than that from observed rainfall. Hence, careful consideration of the error evaluation should be done when making quantitative decisions from forecasted data. The importance of the uncertainty should be accounted for by identifying the range of possible values.

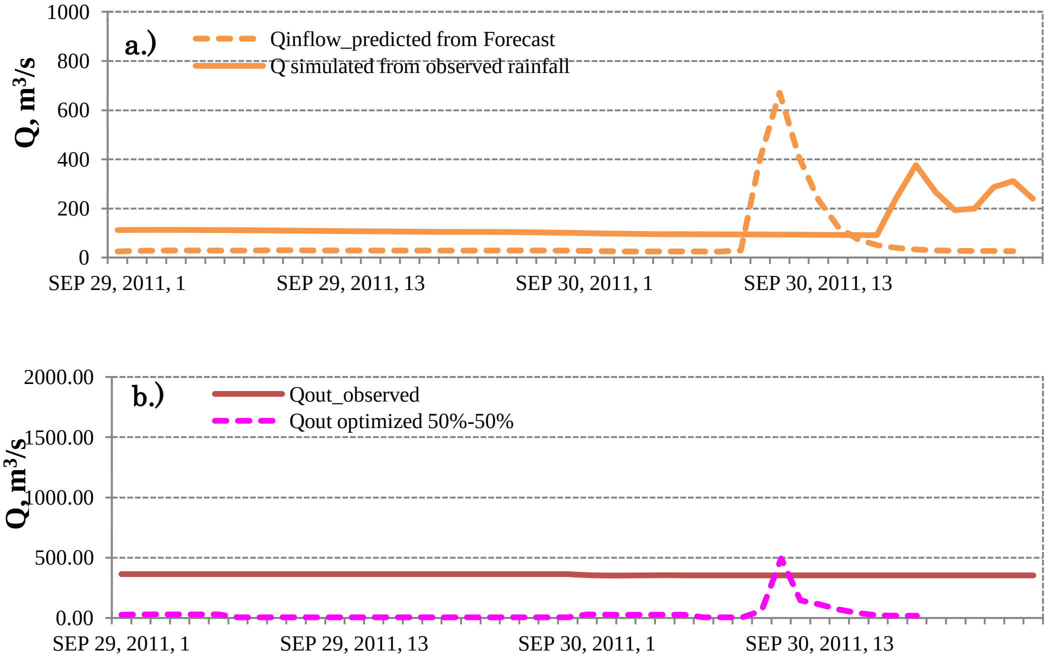


Figure 5.9-2. Typhoon Quiel 6-hourly average of discharge from **a.)** dam inflow and **b.)** dam release.

The simulation using the ensemble members accounts for this difference. For simplification, the average of the ten ensemble members for each 6 hourly time step are summarized in **Figure 5.9-2a** for dam inflows and **Figure 5.9-2b** for optimized dam release. The optimized dam releases are much lower than the observed daily dam release and only increased slightly during the extreme event.

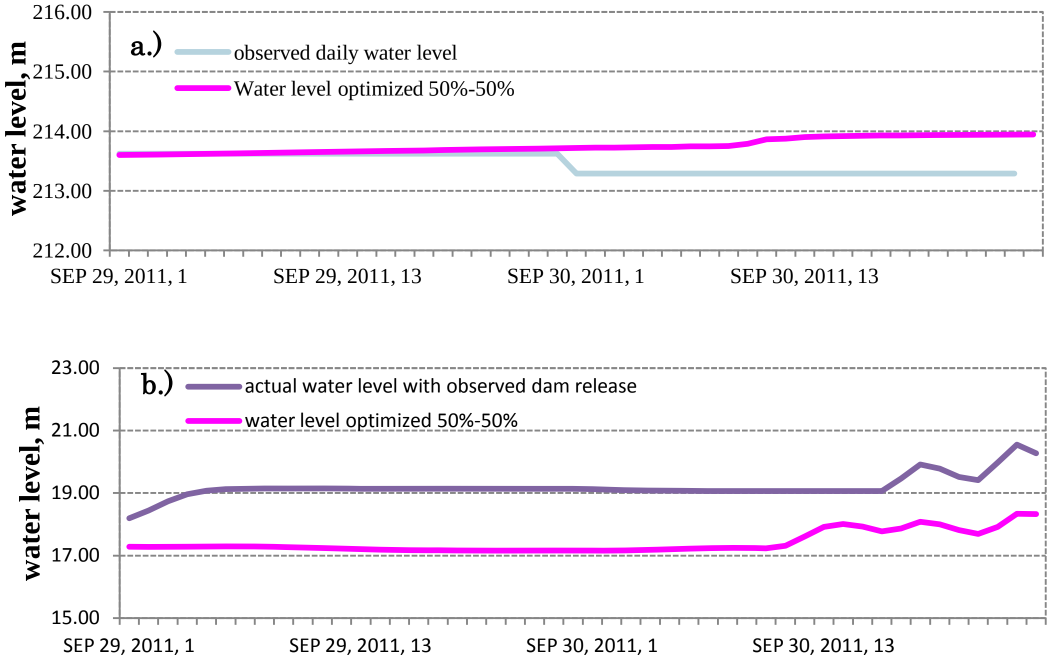


Figure 5.9-3. Typhoon Quiel 6-hourly average of water level from **a.)** upstream and **b.)**downstream.

A summary of the actual observed daily water level and the average of the 10 ensemble members 6-hour optimized water level at 50%-50% priority are given in **Figure 5.9-3a** at 214m dam reservoir limit while maintaining the downstream water level at 33.3m. **Figure 5.9-3b** shows how much lower the water level downstream using the optimization scheme is as compared to the water level when actual observed dam release is used. Water level downstream is significantly lower. On a side note, it is during typhoon Quiel that the downstream areas experienced flooding due to saturated soil conditions. If a decision similar to this prioritization is given and the forecast given ahead of time, flood damages can be minimized.

5.10 Case Study 2: Tropical Depression Ramon at 214m Water Level Limit with Observed Dam Release and 50% Priority on Flood and 50% Priority on Water Storage

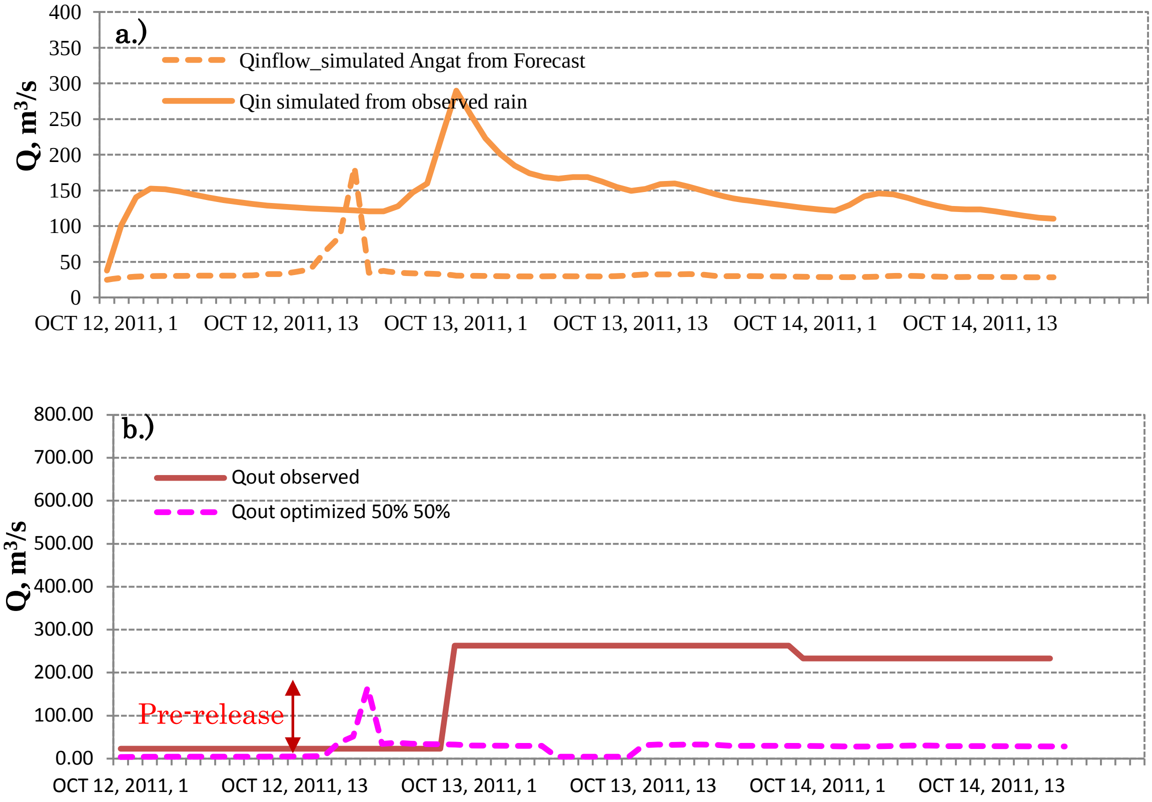


Figure 5.10-1. Tropical Depression Ramon 6-hourly average of discharge **a.)** dam inflow and **b.)** dam release.

Similar to typhoon Quiel, tropical depression Ramon results are also given as averages of the simulated 6-hourly forecasts from the ten ensemble members. However, contrary to the case on Quiel, the simulated peak discharges from dam inflows using observed rainfall are much higher than the simulated forecast inflows. This results to much lower optimized dam releases than the daily observed dam releases by the NIA. However, note that a pre-release (**Figure 5.10-1b**) prior to reaching the water level limit in the reservoir is suggested in the optimized condition (**Figure 5.10-2a**). Additionally, the water level in the reservoir in **Figure 5.10-2a** is maintained below the 214m limit. This is an improvement as compared with the observed daily water level by NIA that reached up to 214.25m on the second day. The water level downstream is also improved (**Figure 5.10-2**) since the actual water level downstream was continuously higher than the optimized downstream water levels. This indicates that using this 50% priority on flood and 50% priority on water storage scheme, the flood risk downstream that may be caused by tropical depression Ramon may be minimized.

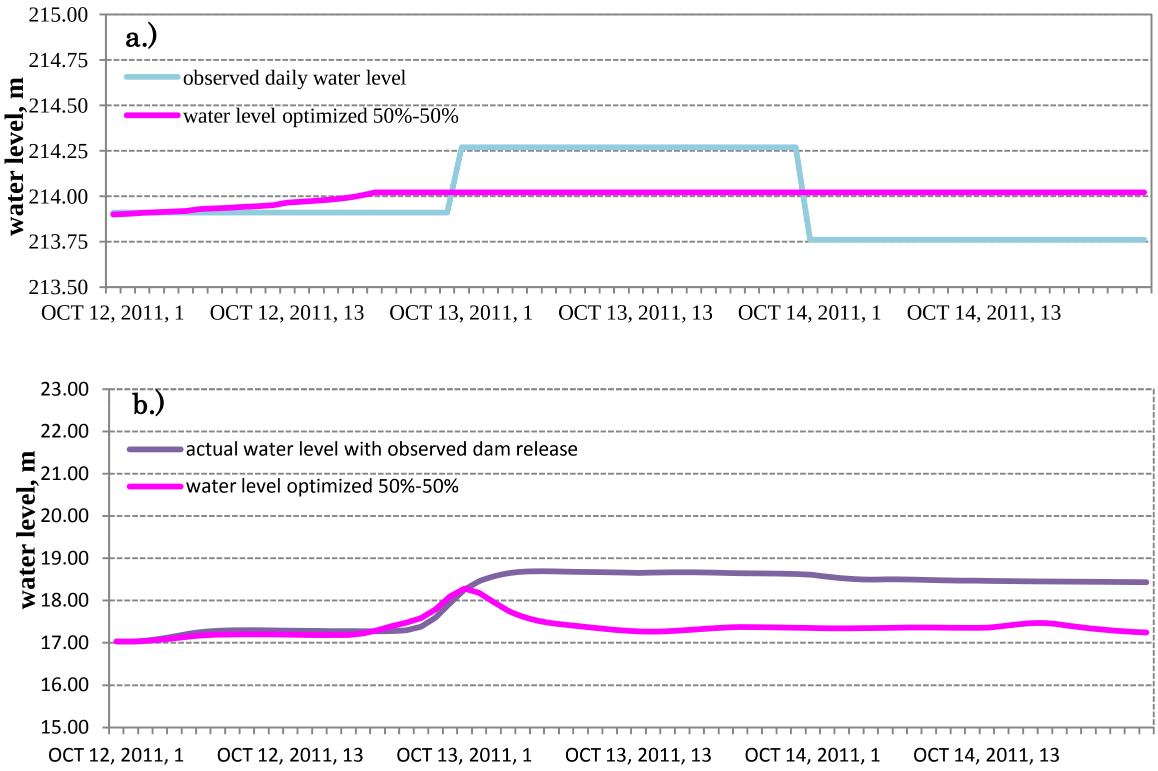
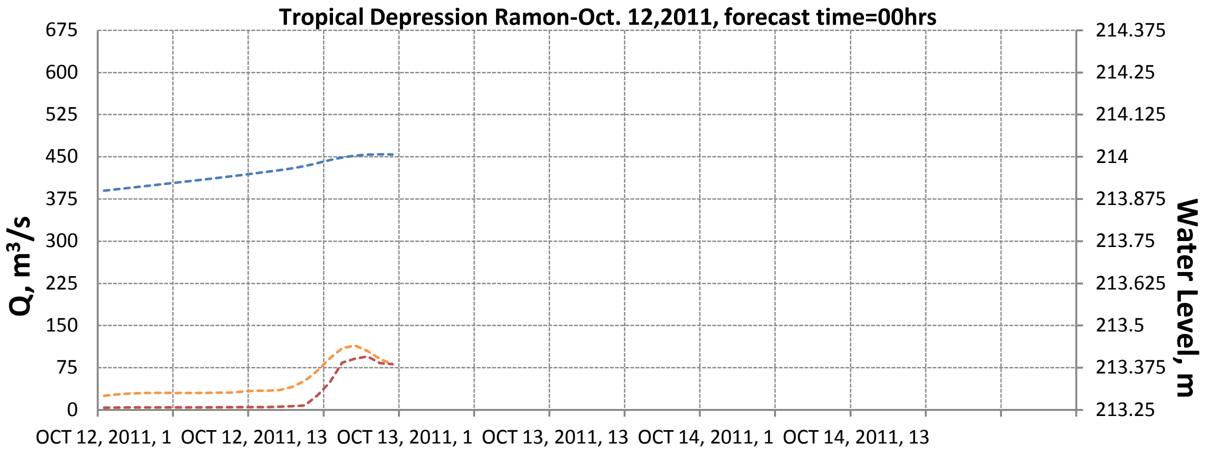
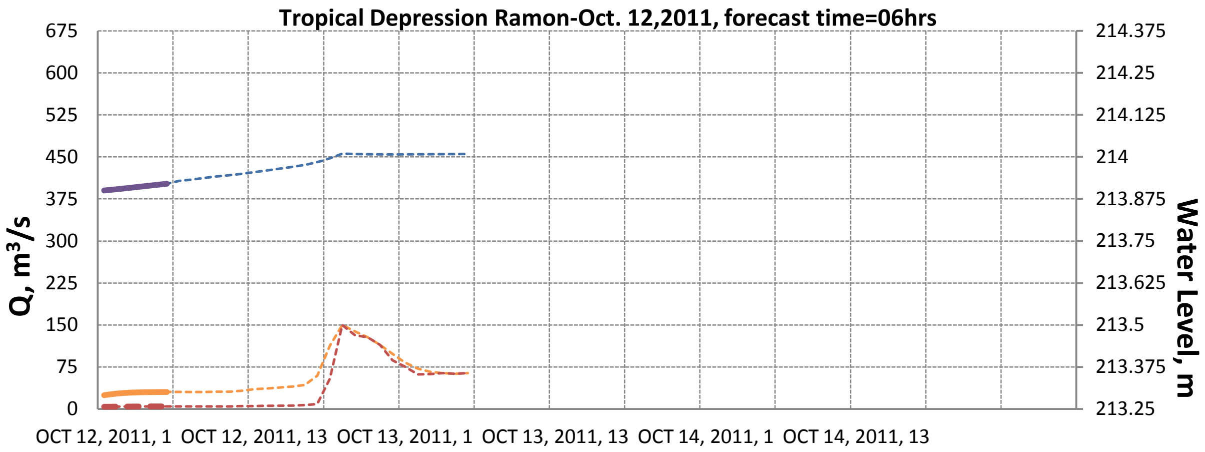


Figure 5.10-2. Tropical Depression Ramon 6-hourly average of water level from **a.)** upstream and **b.)** downstream.

The succeeding figures in **Figure 5.10-3** show how the average of the 10 ensemble members (24-hour forecast shown as broken lines) for water level in the reservoir, dam inflow and optimized dam outflow, behave for each of the 6-hour prediction time interval during Tropical Depression Ramon. Successful dam optimization is observed below the 214m water level limit, above which, dam inflows are completely released as dam outflows (October 12, 2011, forecast time = 18:00hrs).





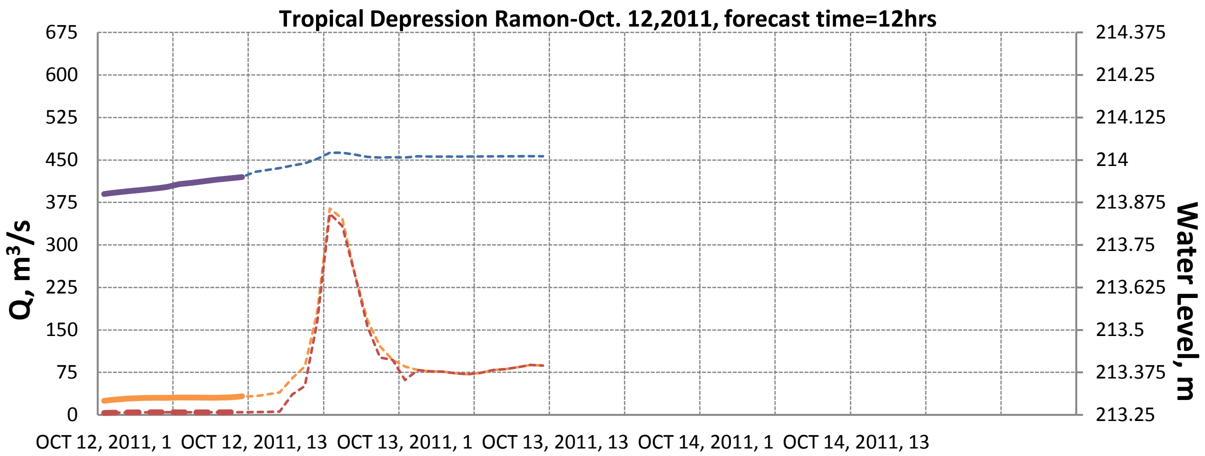


Figure 5.10-3. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for Tropical Depression Ramon with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)

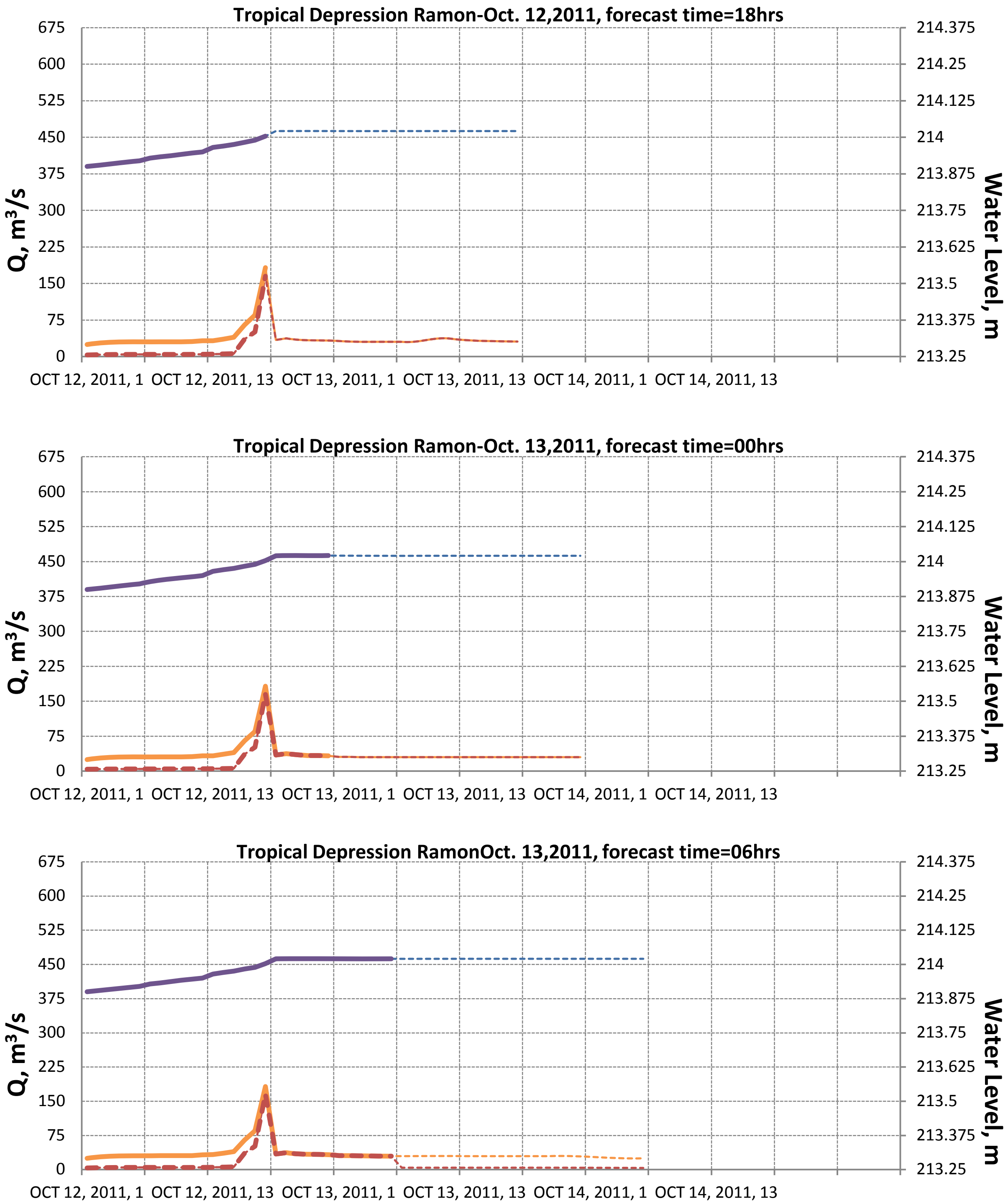
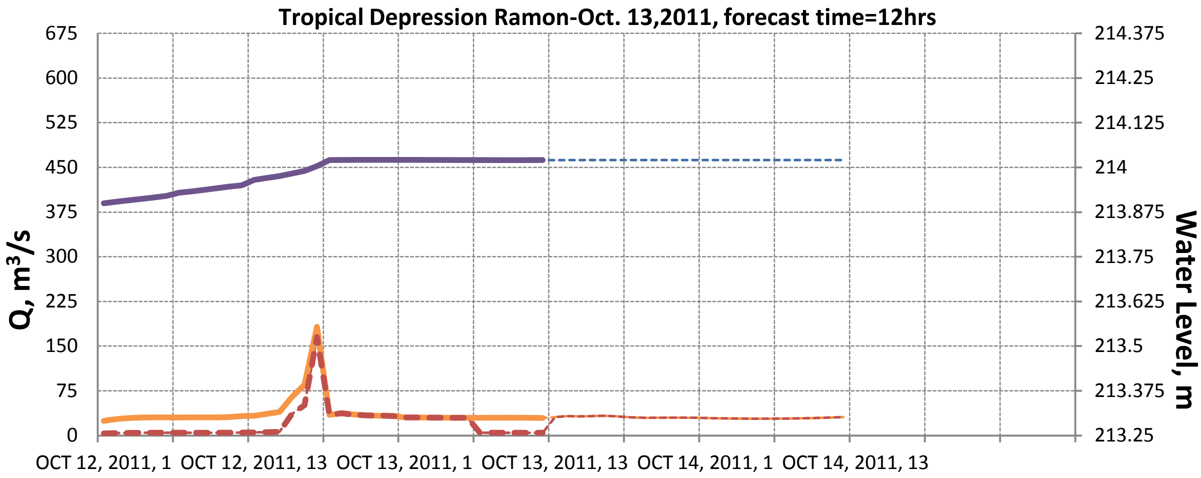


Figure 5.10-3. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for Tropical Depression Ramon with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)



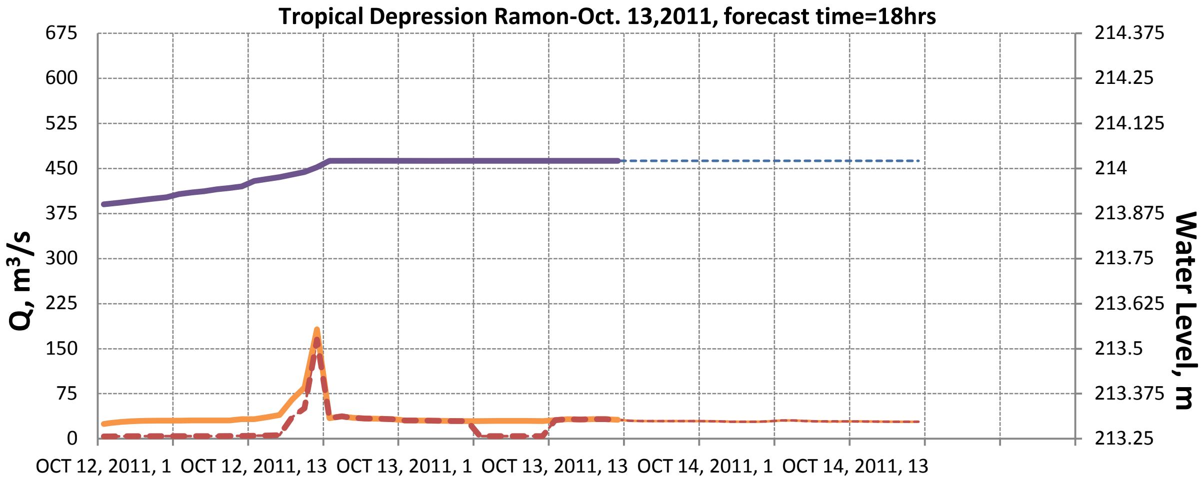
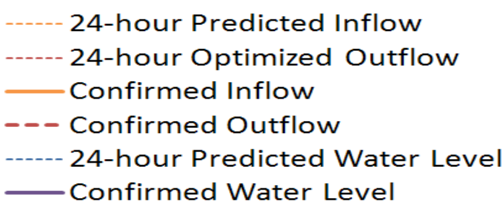


Figure 5.10-3. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for Tropical Depression Ramon with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps[see legend below])



5.11 Case Study 3: Typhoon Pedring at 214m Water Level Limit with Observed Dam Release, with 0% Priority on Flood and 100% Priority on Water Storage; 20% Priority on Flood and 80% Priority on Water Storage, 50% Priority on Flood and 50% Priority on Water Storage

When it comes to decision making, there is a very high uncertainty on which dam function should be prioritized. There is also a very high uncertainty on whether the final decisions will avoid unnecessary conflicts between the different sectors benefiting the water from the dam. In this case study, we do not attempt to solve the decision making uncertainties but instead provide possible alternative decisions on which function to prioritized to show how the dam optimization scheme can operate in the different sample priority schemes. **Figure 5.11-1** shows the simulated dam inflows using observed hourly gauge rainfall data (solid line) versus simulated dam inflow using forecast rainfall (broken line). This figure shows that for typhoon Pedring, the model shows very similar ensemble average peak discharge. The overestimates and the time delays for the peaks to be simulated indicate that the forecast data and the gauge rainfall data has some error thus careful consideration of uncertainty should also be considered for this case.

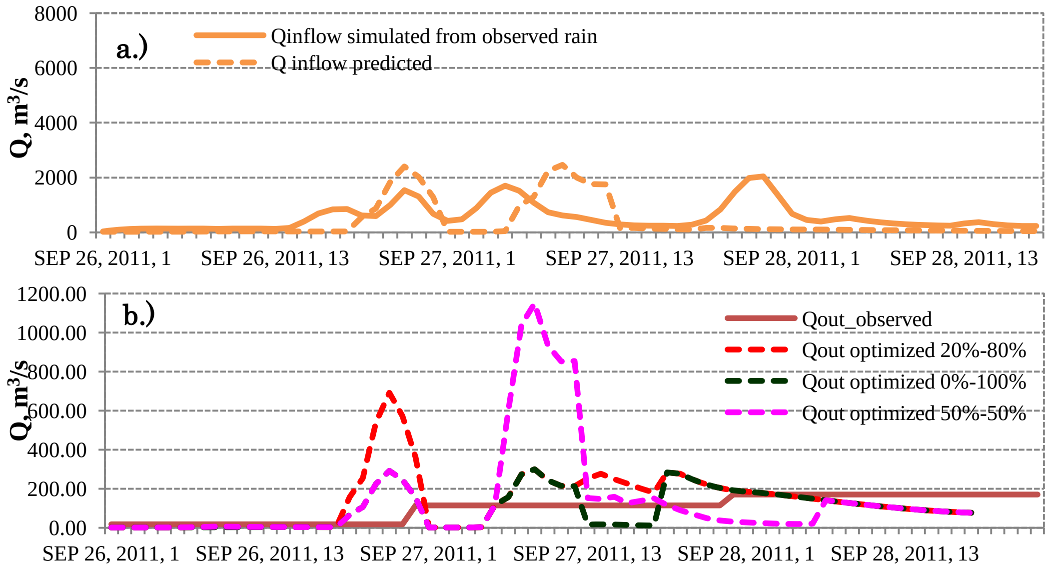


Figure 5.11-1. Typhoon Pedring 6-hourly average of **a.)** dam inflow and **b.)** dam outflows from the different priority schemes.

In Figure **5.11-2a**, the water level in the upstream with no dam release is the highest possible value of water level if all the water is stored. The water level with actual daily dam release is the water level with no dam release minus the daily observed outflow (by NIA). This water level should theoretically be similar to the daily observed water level if total rainfall is not underestimated. Unfortunately, some underestimation due to missing gauges happened during typhoon Pedring so for comparison, the water level with observed daily release will be used as a basis of comparison with the different prioritization schemes in Case study 3.

A mass balance of the water into and out of the dam and the corresponding maximum water level is listed below.

Initial Volume = 635MCM

Initial Water Level = 206.94m

Area Upstream Angat = 470 sq. km.

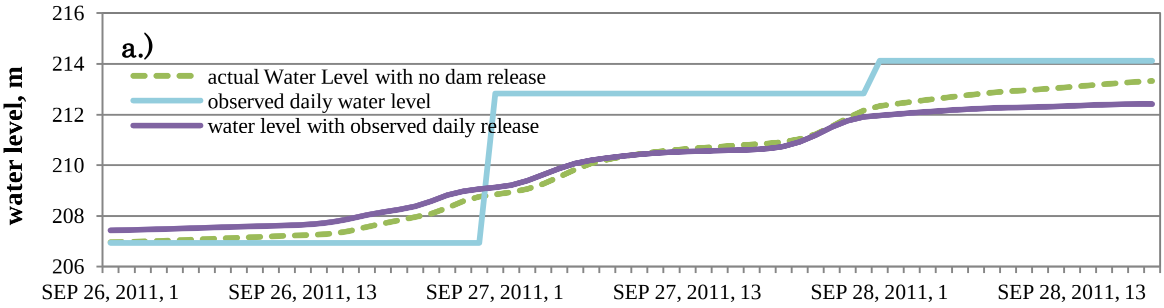
Rainfall from Angat for 3 days =335 mm(NPC, hourly)

Volume from rain = 335mm*470sq.km*1m/1000mm*1000m/km*1000m/km=157.45MCM

Dam release volume = 8.42+9.36+22.94 = 40.72MCM

BALANCE = 635MCM+157.45MCM-40.72MCM= 751.73MCM ==212.6m to 212.7m

In Figure **5.11-2b**, the actual water level with observed dam release is considered as the basis of comparison for the three priority schemes.



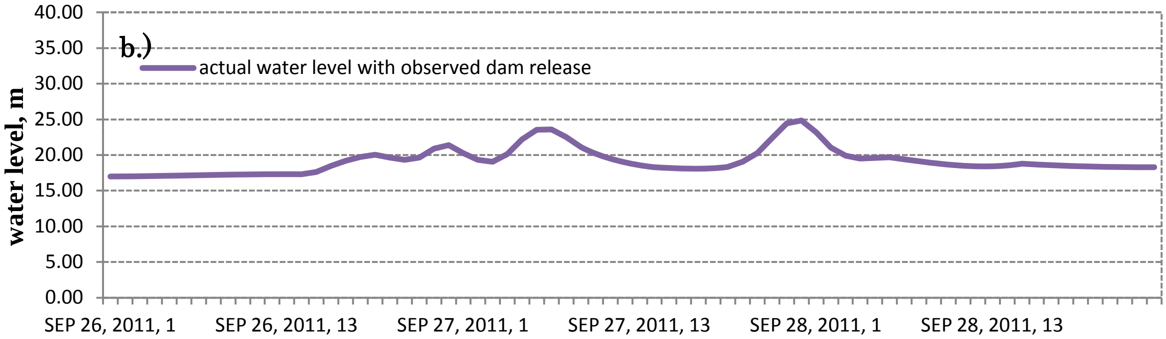


Figure 5.11-2. Typhoon Pedring average water levels from **a.)** upstream with dam release, with no dam release and with actual observed daily release and **b.)** downstream actual water level with observed daily dam release.

5.11.1 Typhoon Pedring at 0% Priority on Flood 100% Priority on Water Storage

The dam release from the priority scheme 0%-100% is given in **Figure 5.11-3**. These releases are similar in intensity to the daily dam releases but done only on the few hours that water level needs to be optimized.

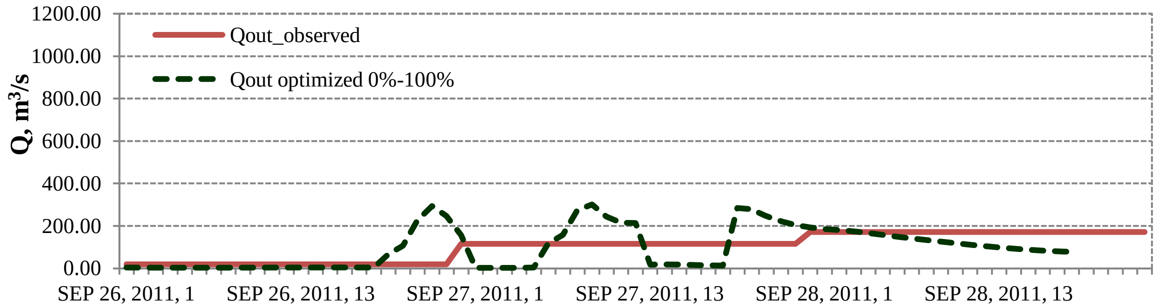


Figure 5.11-3. Typhoon Pedring 6-hourly average of dam release from daily observed and 0%-100% optimization scheme.

The water levels upstream and downstream for this scheme is given in **Figure 5.11-4a** and **Figure 5.11-4b**. Note that the priority of this scheme is only on trying to keep the water upstream of the reservoir to as high as possible, hence it is expected that the optimization scheme will have similar results as the water level with observed daily release. Consequently, the downstream water level will only be slightly different from that of actual downstream water level with observer dam release.

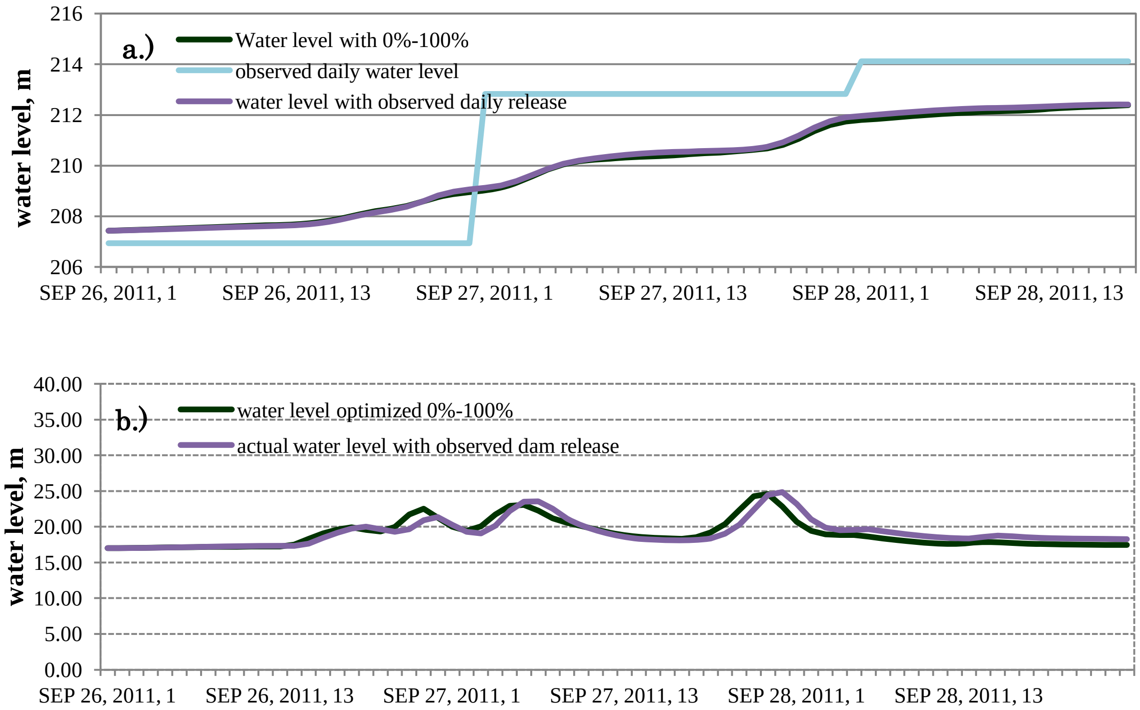
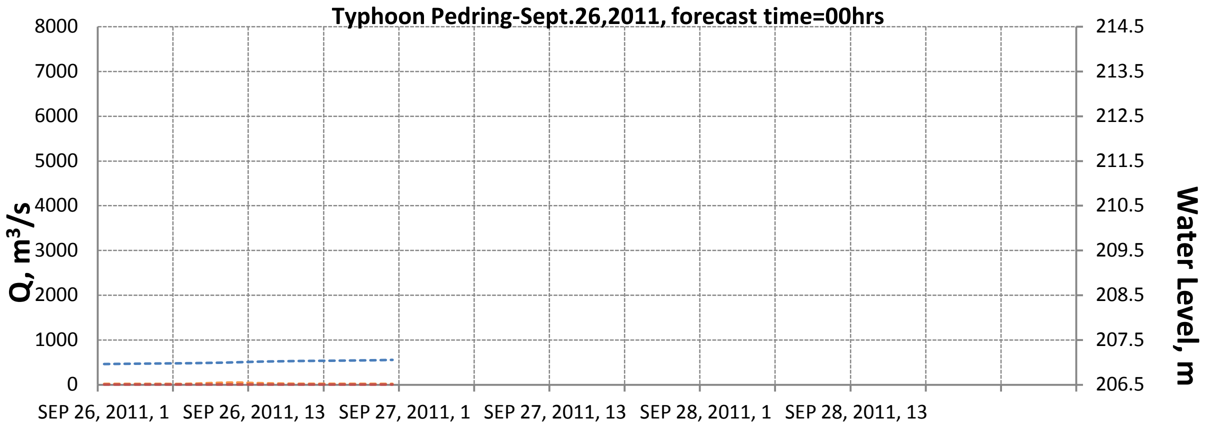
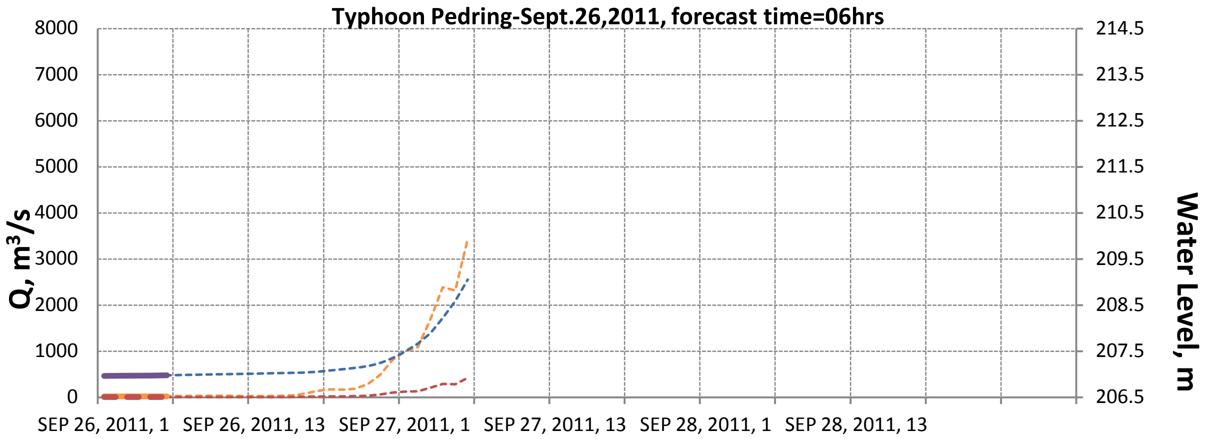


Figure 5.11-4. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)**downstream.

The succeeding figures in **Figure 5.11-5** show the average of the 10-ensembele members (24 hour forecast shown as broken lines) for each of the 6 hourly prediction time interval for water level, dam inflow and optimized dam outflow for typhoon Pedring with 0% priority of flood and 100% priority on water storage at dam reservoir maximum limit at 214m.





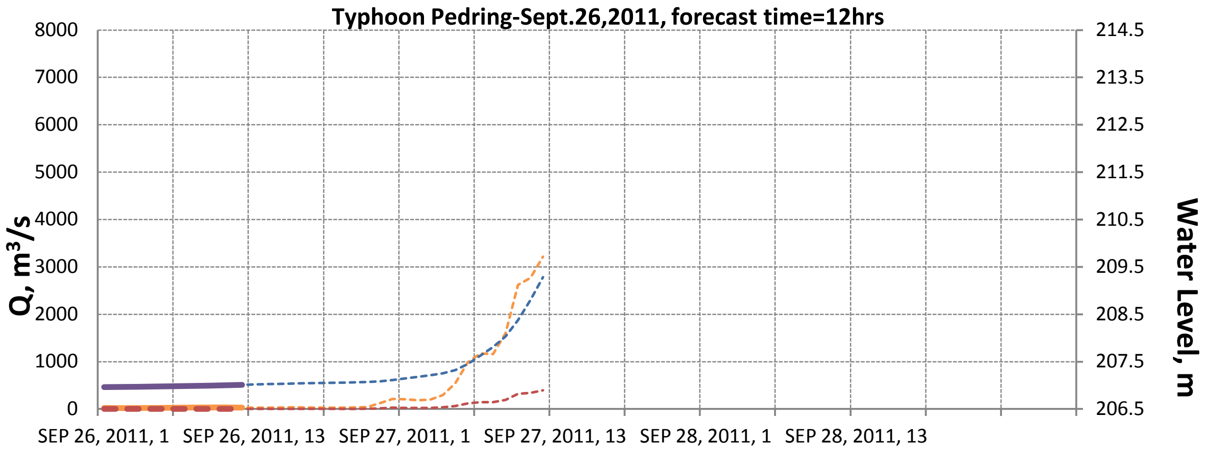
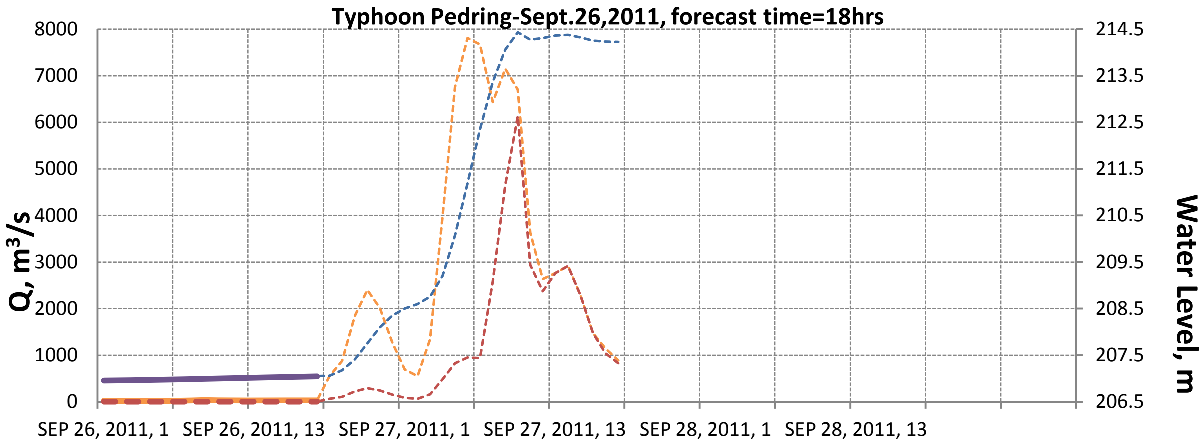
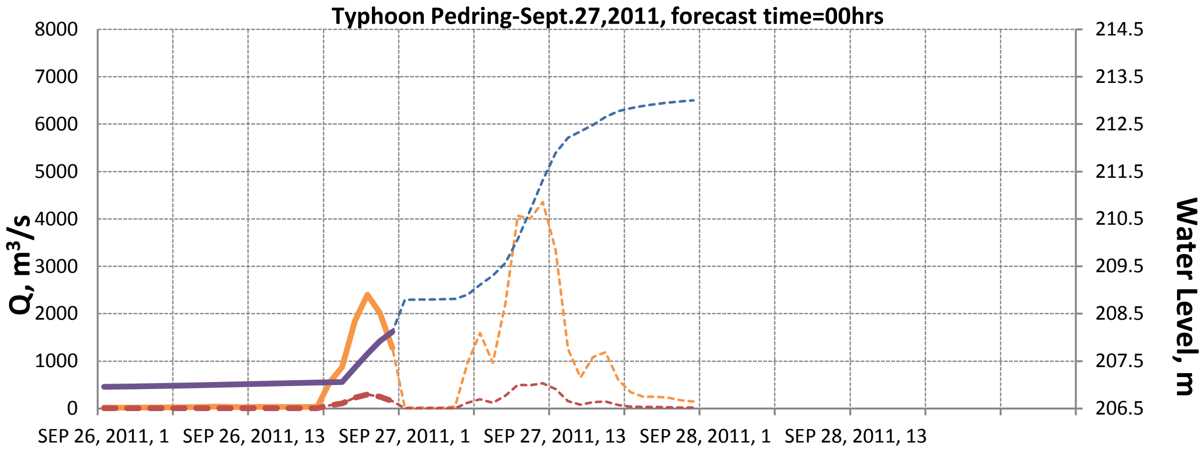


Figure 5.11-5. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 0% priority on flood and 100% priority on water storage at dam reservoir maximum limit at 214m. (cont.)





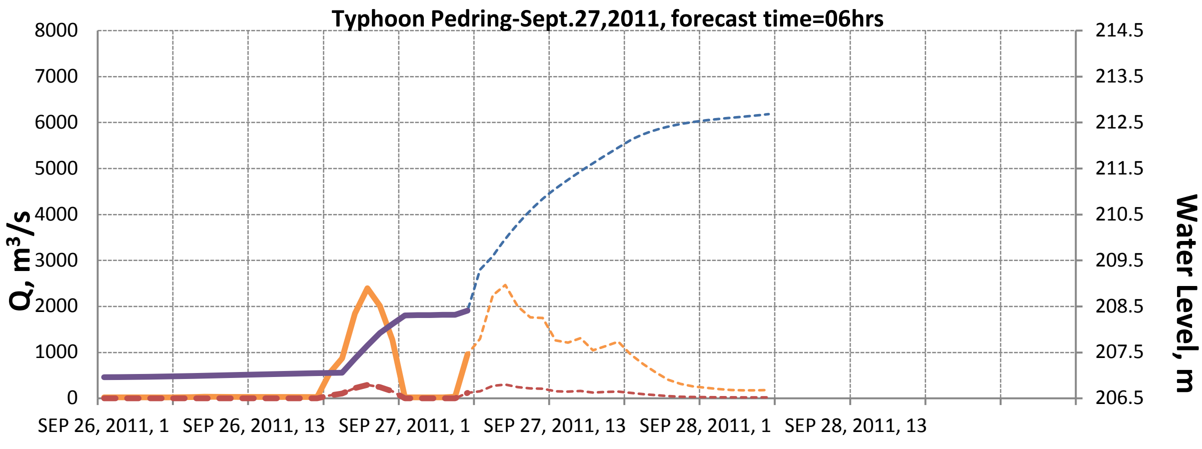
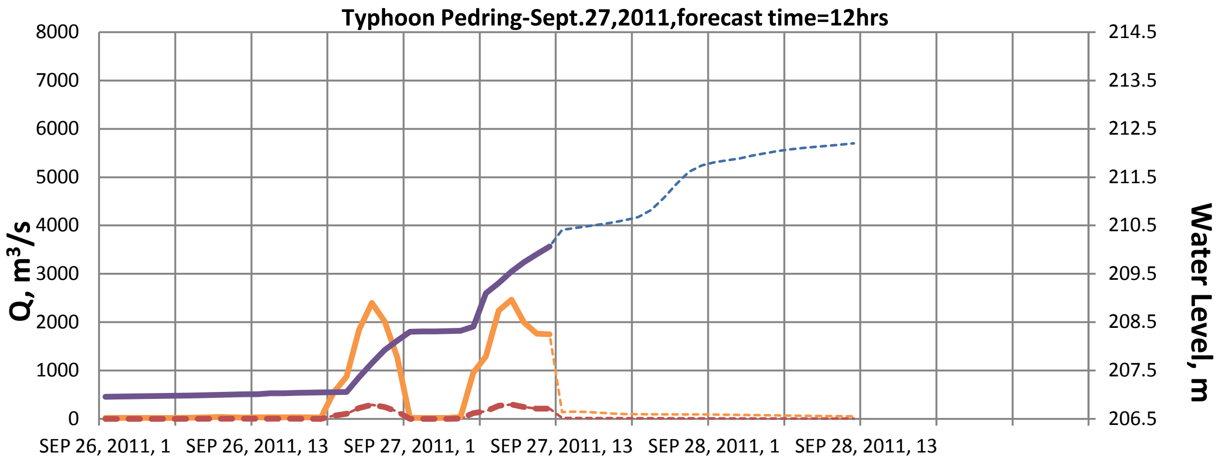


Figure 5.11-5. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 0% priority on flood water storage and 100% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)



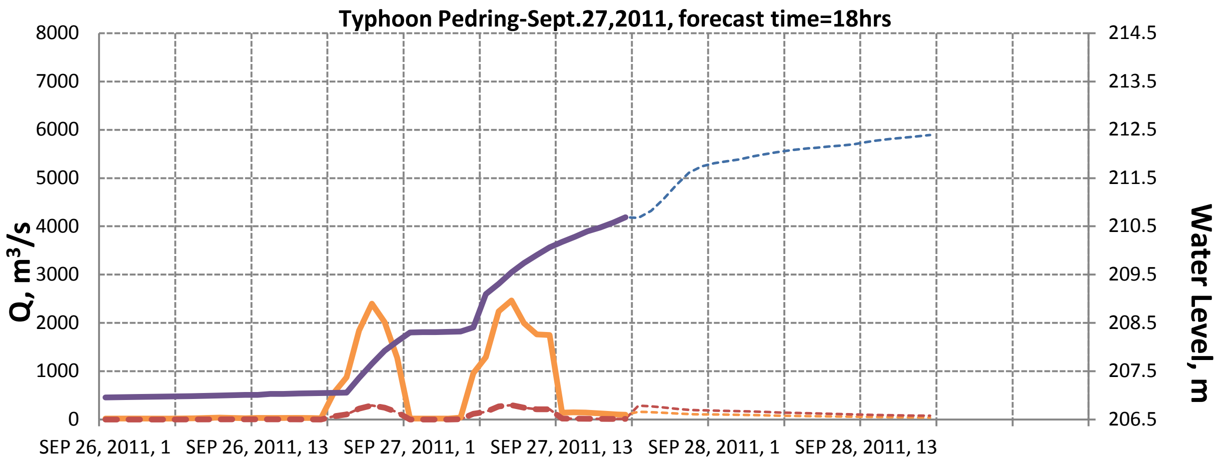
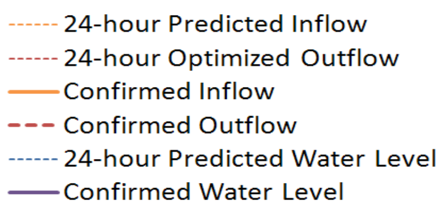


Figure 5.11-5. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 0% priority of water storage and 100% priority on flooding downstream with dam reservoir maximum limit at 214m. (Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps [see legend below])



5.11.2 Typhoon Pedring with 20% Priority on Flood 80% Priority on Water Storage

A different priority scheme is presented here in that 20% priority is for maintaining the water level downstream below the critical water level of 33.3m and 80% priority on keeping the water level in the dam reservoir to below the 214m limit. The dam release (**Figure 5.11-6**) for this scheme has a much larger pre-release since it can allow 20% priority on keeping the water level below 33.3m downstream. Since the level downstream is not yet reached, higher dam release occurs on September 26 (Note that this is prior to the large expected discharge on September 27.

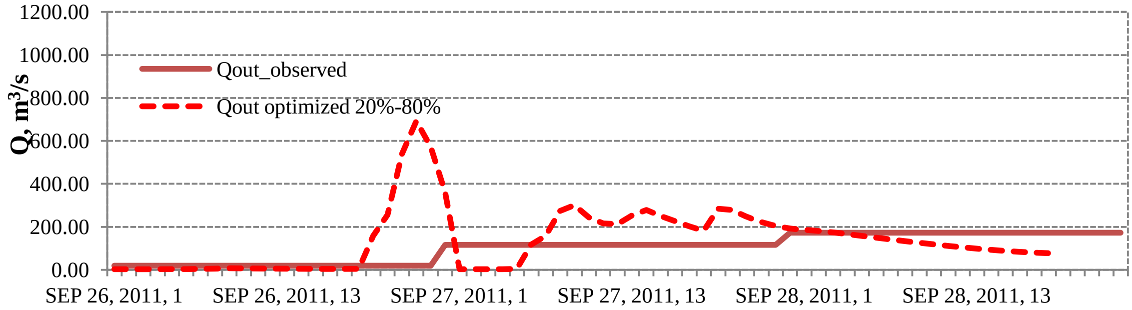


Figure 5.11-6. Typhoon Pedring 6-hourly average of dam release from daily observed and 20%-80% optimization scheme.

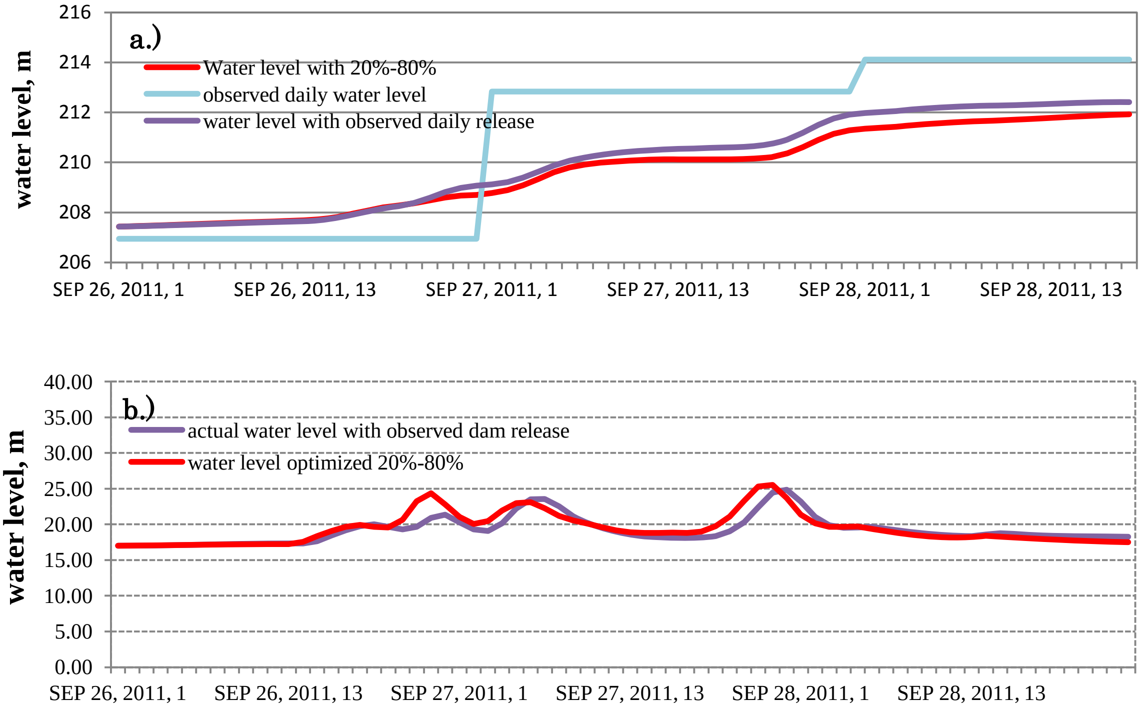
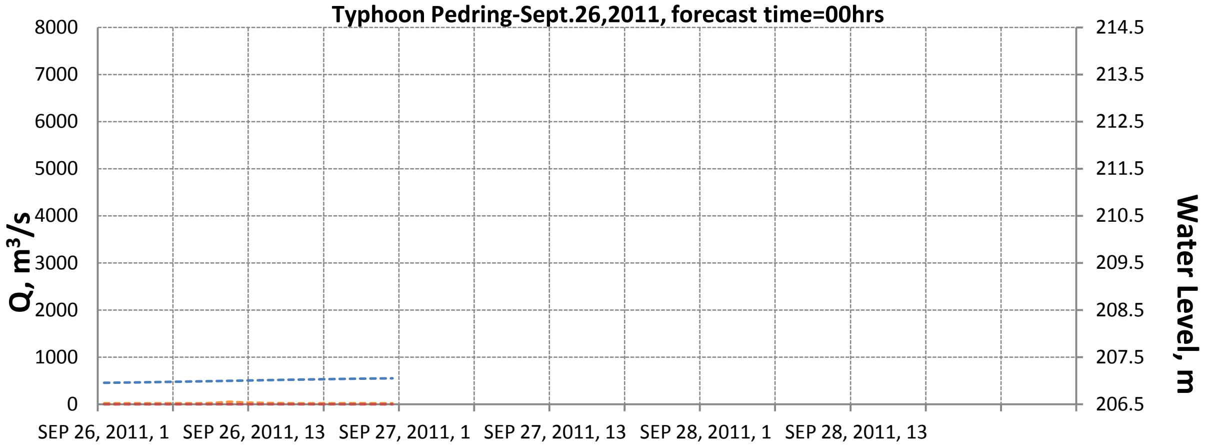
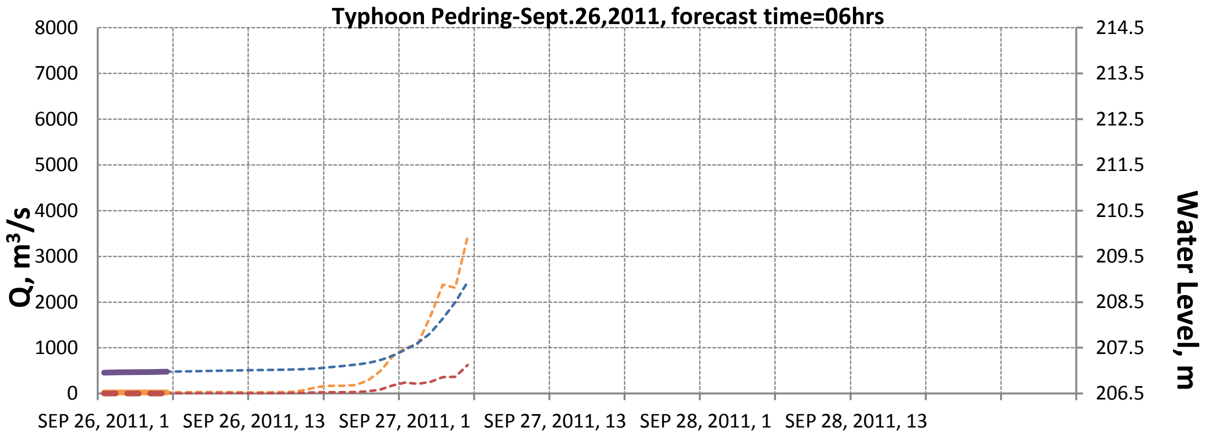


Figure 5.11-7. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)**downstream.

Consequently, the water levels upstream in the dam reservoir is much lower (**Figure 5.11-7**) than that with actual daily release since more release is permitted to exit the reservoir. This higher pre-release affects the downstream Matictic water level by slightly increasing the water level downstream especially on September 26th.

The average of the 10 ensemble members for water level, dam inflow and optimized outflow for the 20% priority on flood-80%priority on water storage are given in Figure **5.11-8** for typhoon Pedring.





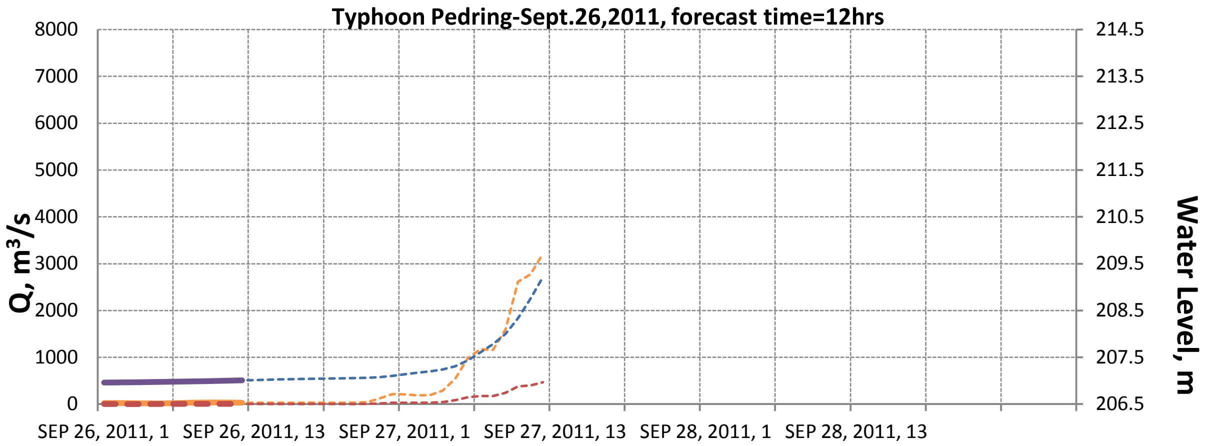


Figure 5.11-8. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 20% priority of water storage and 80% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)

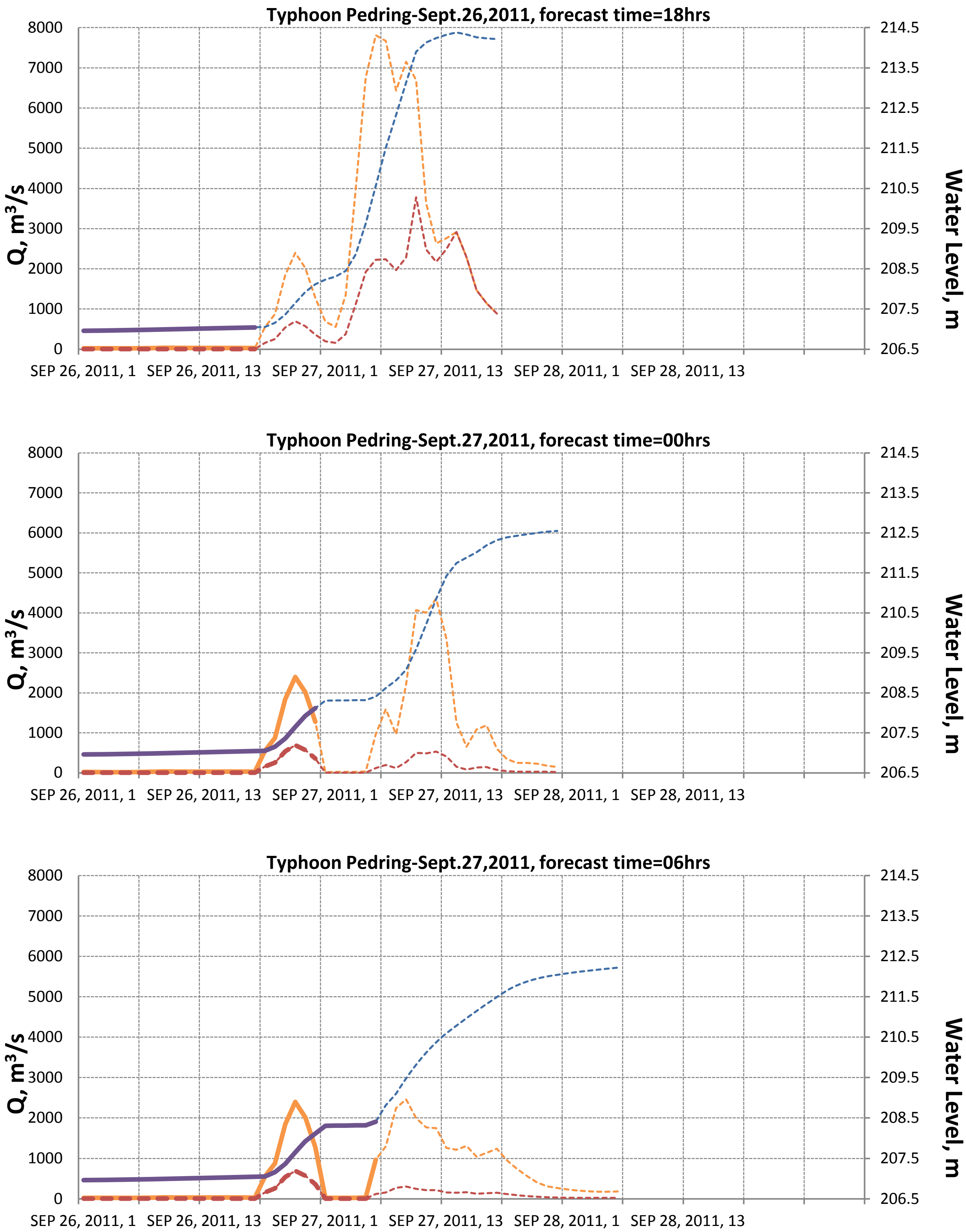
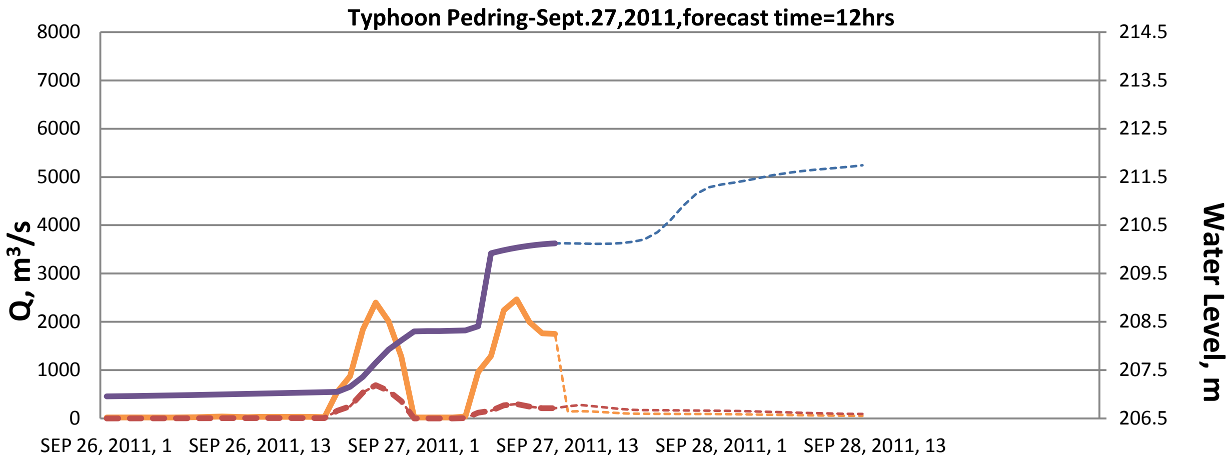


Figure 5.11-8. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 20% priority of water storage and 80% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)



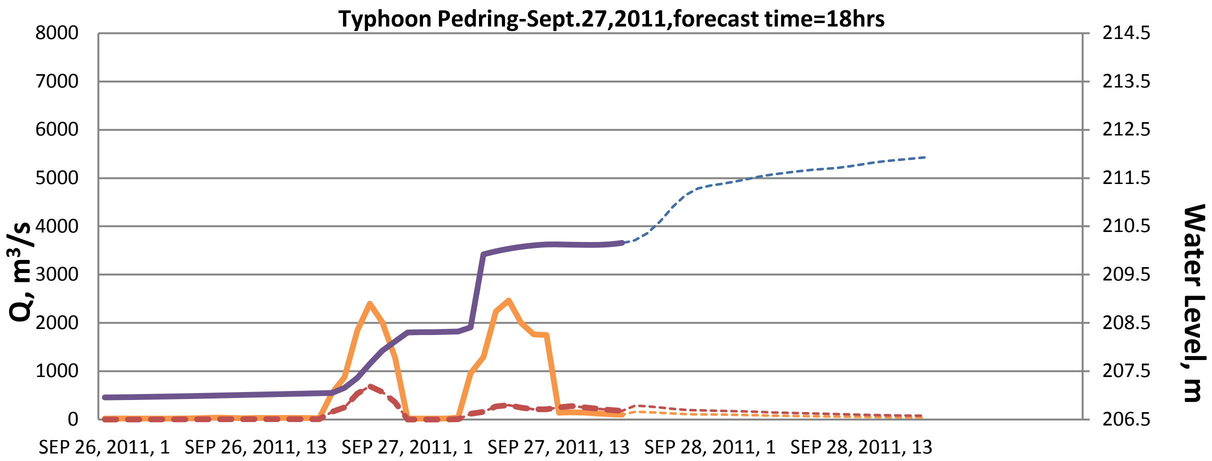
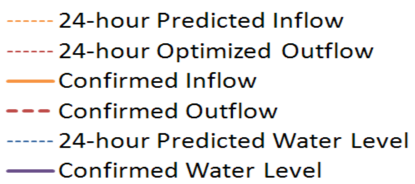


Figure 5.11-8. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 20% priority of water storage and 80% priority on flooding downstream with dam reservoir maximum limit at 214m.

Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps [see legend below].



5.11.3 Typhoon Pedring with 50% Priority on Flood 50% Priority on Water Storage

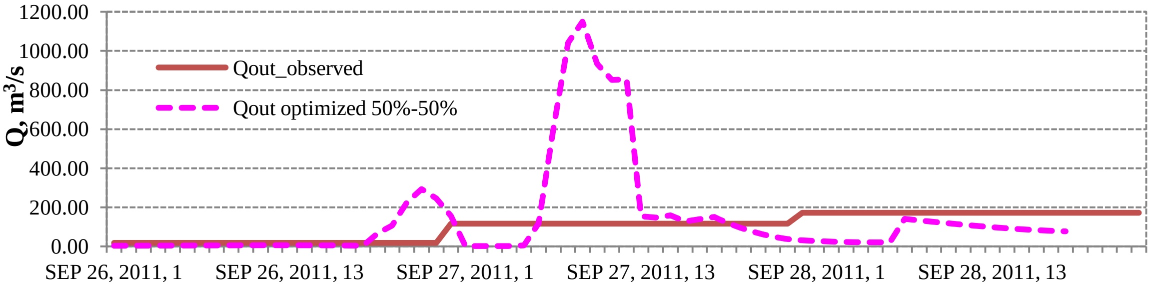


Figure 5.11-9. Typhoon Pedring 6-hourly average of dam release from daily observed and 50%-50% optimization scheme.

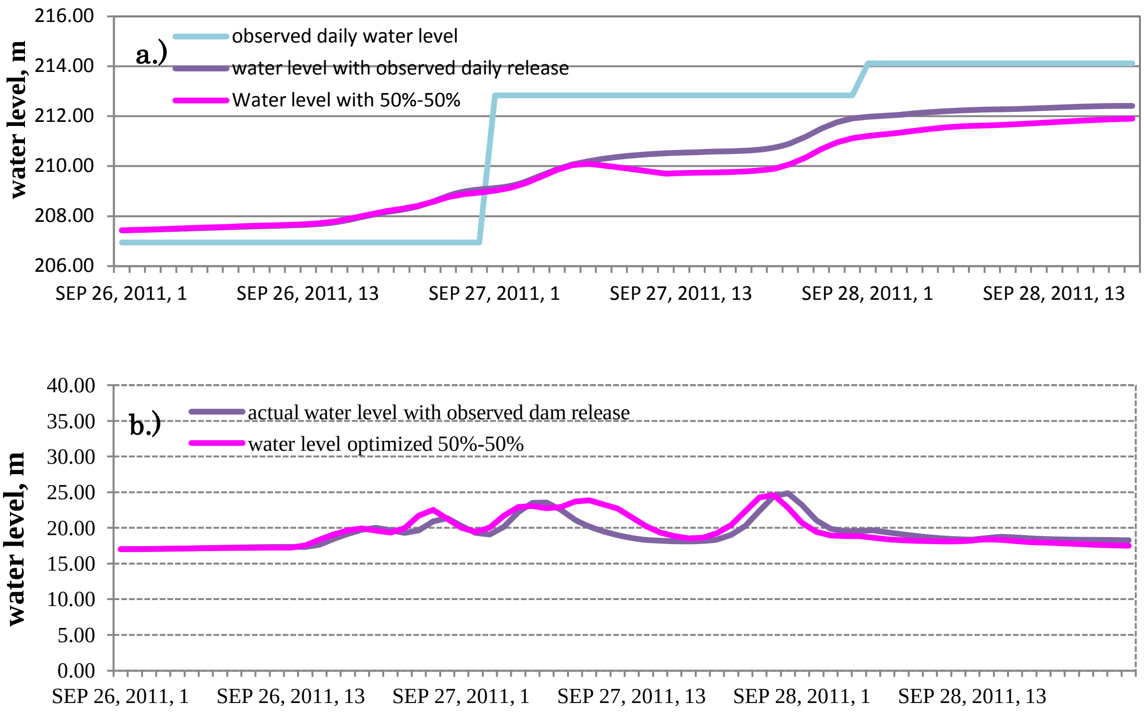


Figure 5.11-10. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)**downstream.

This case is similar to the Case 1 and 2 in that equal priority is given to flood control and water storage. The pre-release in this case is in the latter part of September 26th and September 27th (**Figure 5.11-9)**. Lower releases are permitted on September 28th. These large releases affected the dam reservoir water level in that it is also lower than the water level with daily dam release (**Figure**

5.11-10a). It consequently affected the downstream water level by having high water levels on the second day of the typhoon (**Figure 5.11-10b**).

Figures 5.11-11 show the water levels a.) upstream and b.) downstream for the three priority schemes including water level for observed daily release. The 0%-100% priority scheme is very similar to the water level with observed daily release. The 20%-80% and 50%-50% had almost similar water levels except on some fluctuations on the second day as a result of higher water release from the 50%-50% scheme.

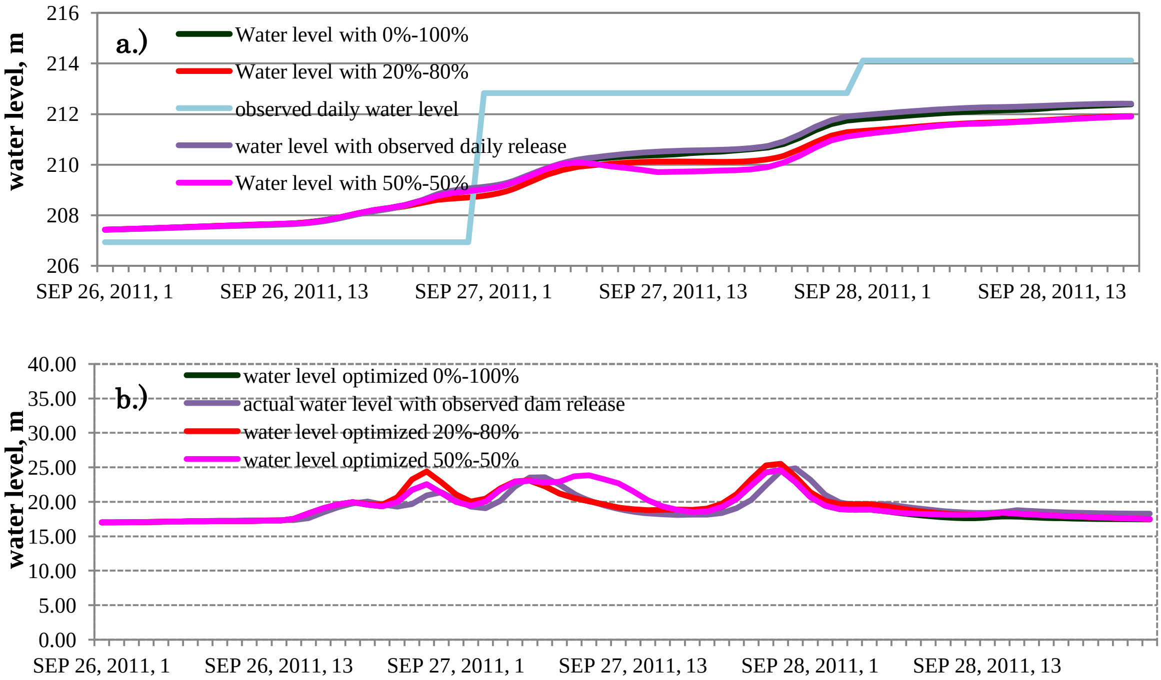
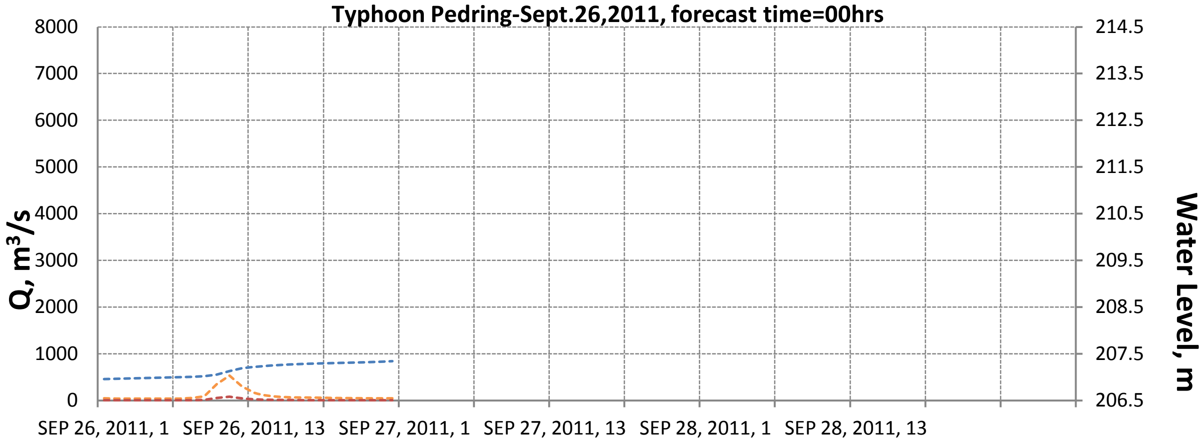
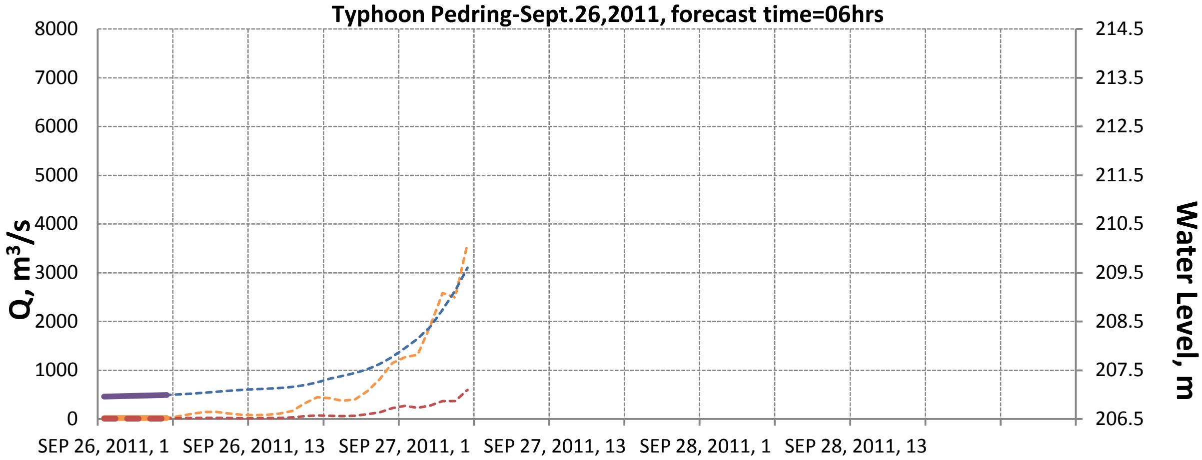


Figure 5.11-11. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)**downstream for all priority schemes.

In all the three priority schemes, none of the water levels reached the maximum limit of 214m. This is due to 1.) The large capacity of the dam reservoir and the low initial water level of 207 m; 2.) the limitation in the number of gauges available to measure hourly rainfall that possibly was not able to capture all the rainfall for the Angat river basin since only two gauges (only Talaguio and Angat and there were times that the gauges were broken during the typhoon). This means that although the priority setting is given, the optimization scheme focused more on storing the water in the reservoir to fill it up to the highest possible water level.





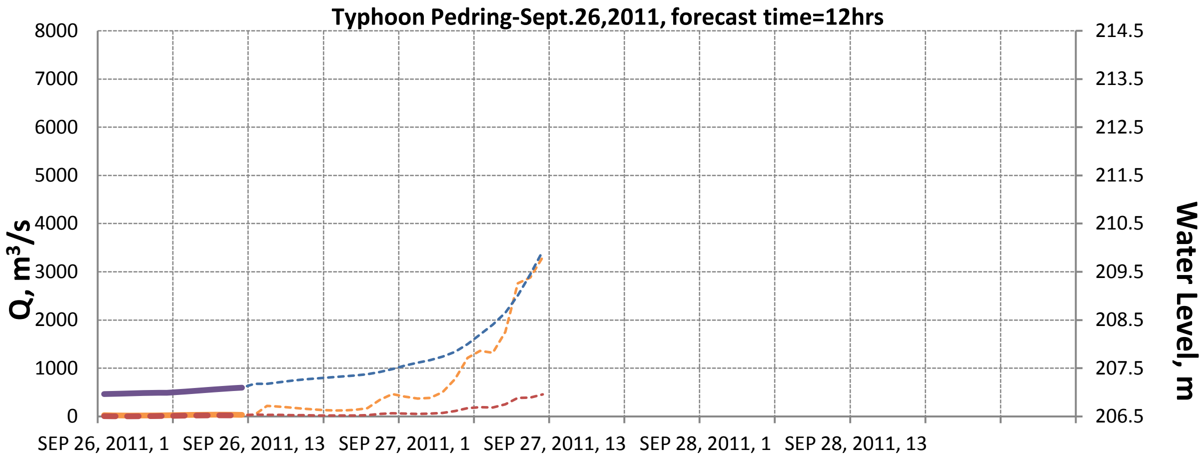


Figure 5.11-12. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)

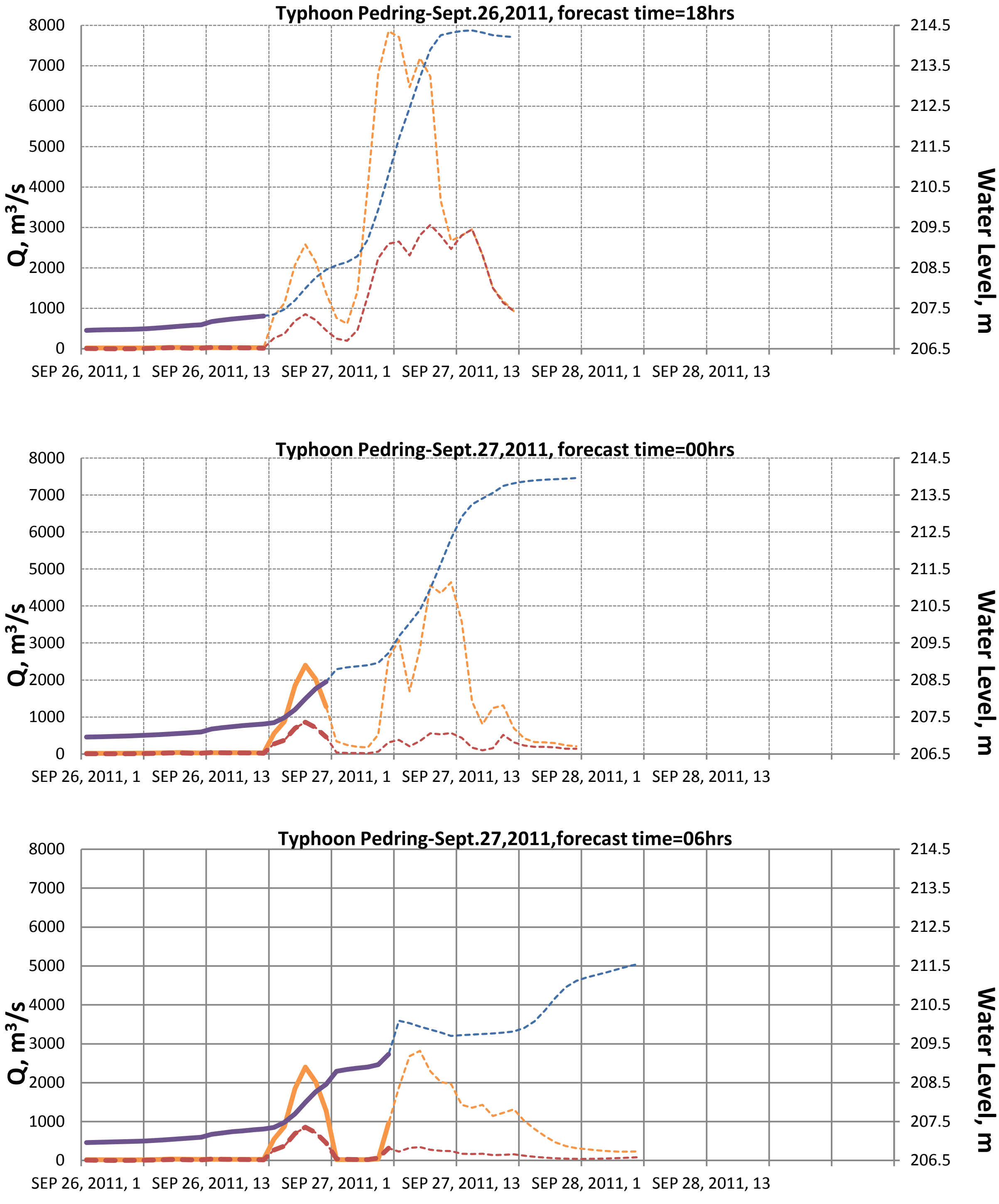
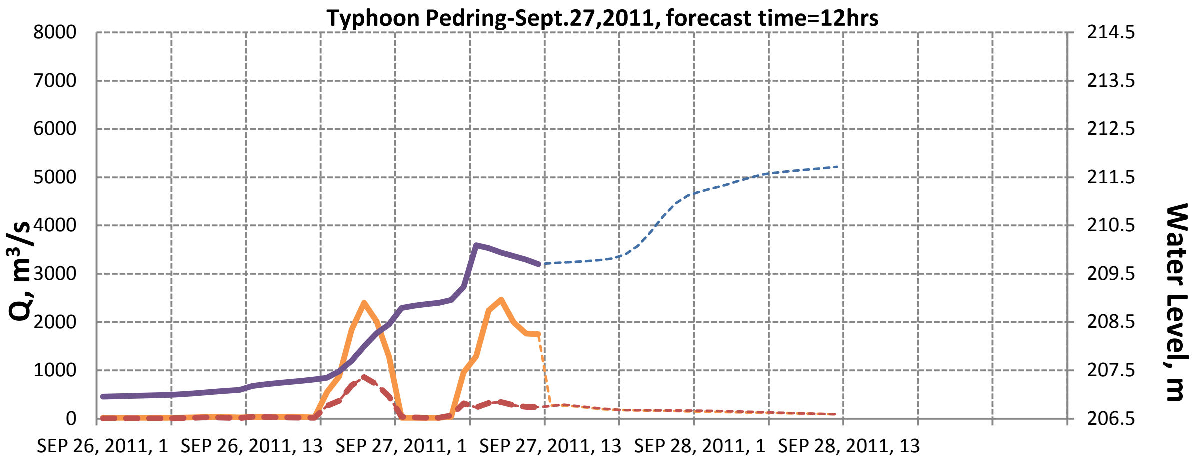


Figure 5.11-12. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. (cont.)



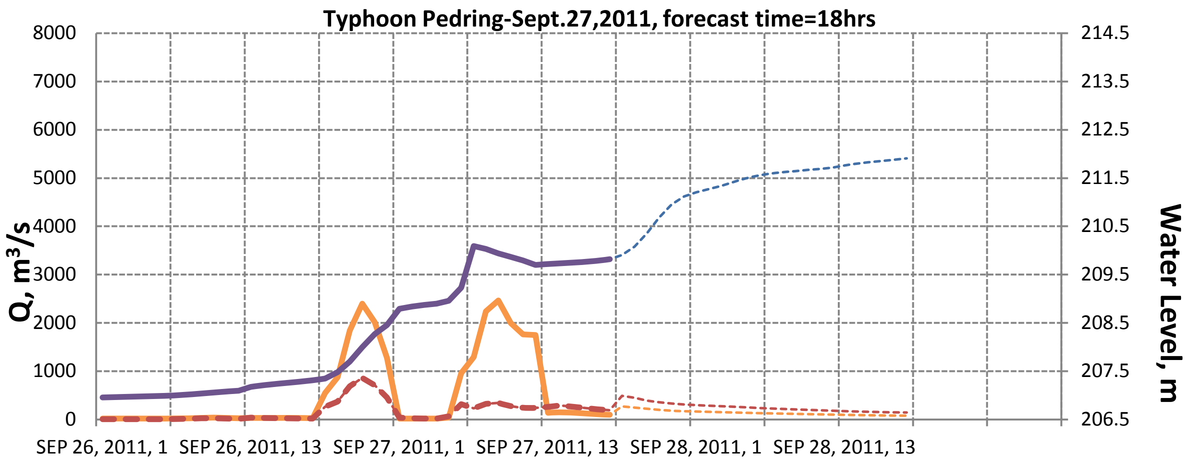
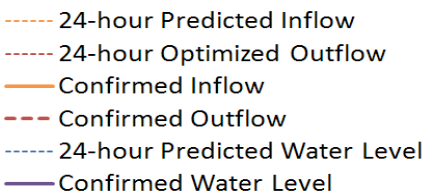


Figure 5.11-12. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m.

(Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps [see legend below])



5.12 Case Study 4: Typhoon Pedring with a Different Initial Water Level at Sept. 26 (from 207m to 212m)

This fourth case assumes a different initial water level on September 26. Thereby reducing the dam reservoir volume capacity. A comparison of this fourth case and the third case at 50%-50% priority is given in Figure **5.12-1**.

Note how the optimized outflow on the fourth time slice from September 26th (18:00) show much higher optimized outflow from the 212m case. This indicates that by this time, the volume of the reservoir is most probably reaching the limit already and therefore is now just releasing all the forecasted inflow to the downstream.

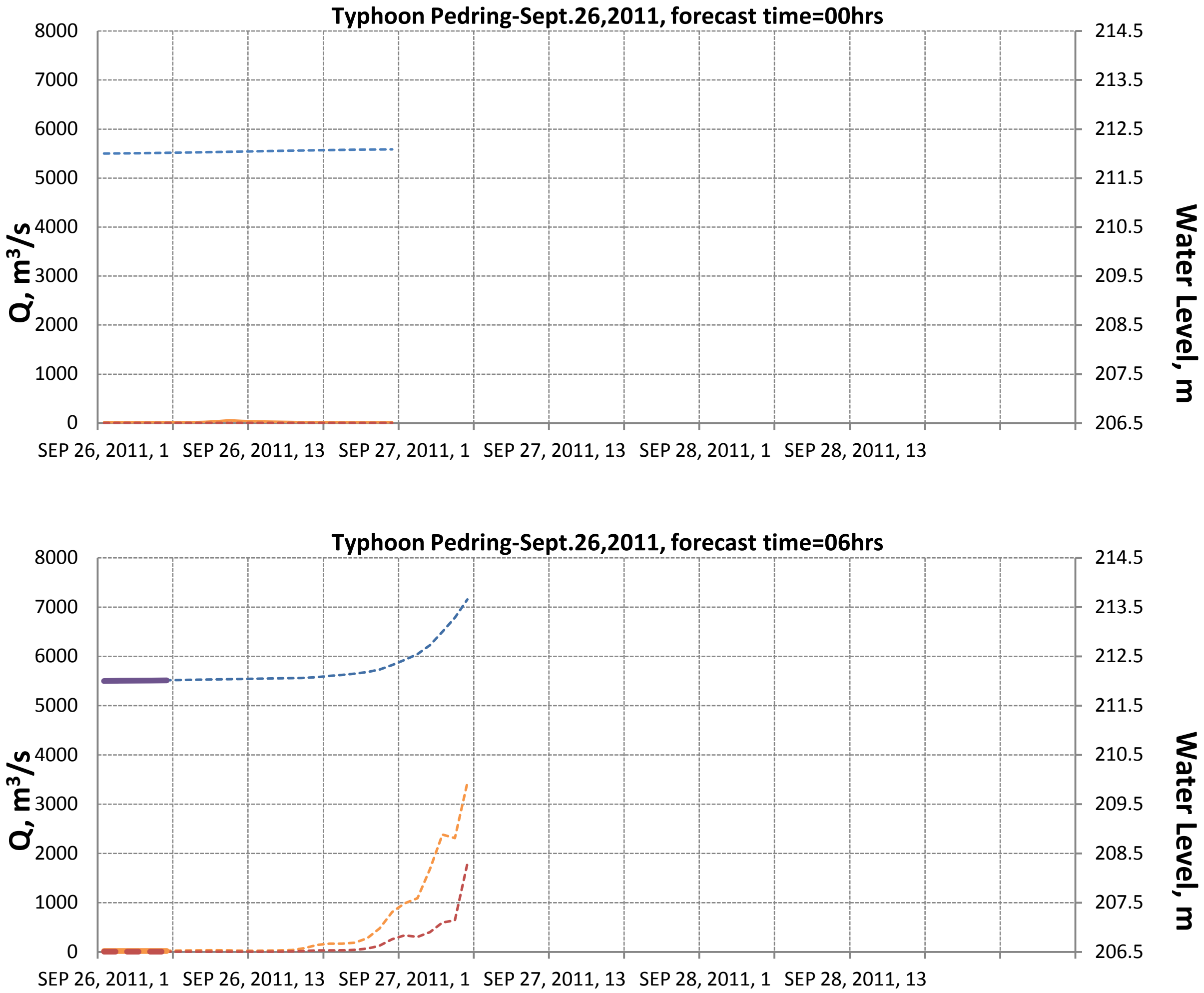


Figure 5.12-1. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. Initial condition is increased from observed 207m to 212m (hypothetical). (cont.)

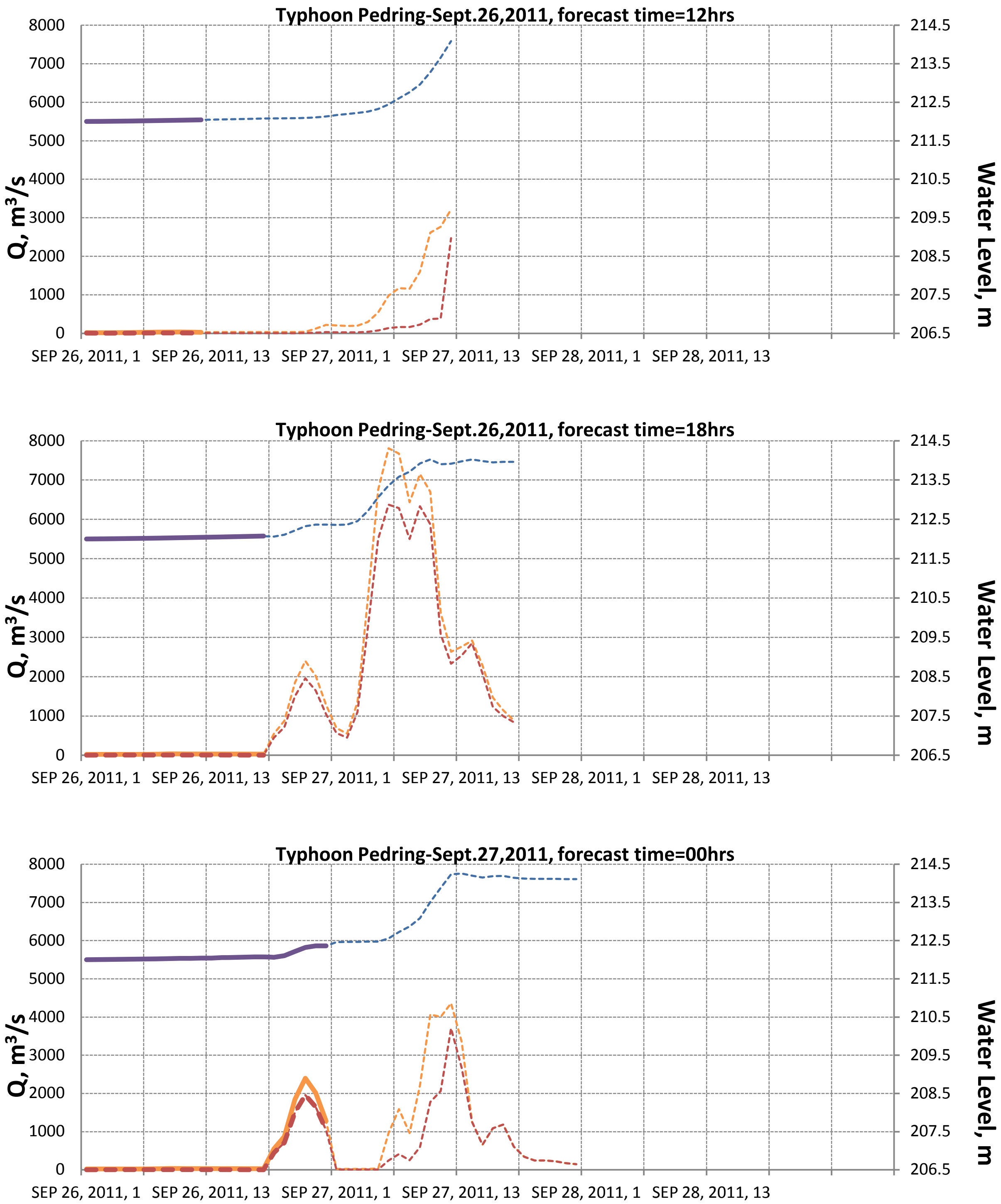


Figure 5.12-1. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. Initial condition is increased from observed 207m to 212m (hypothetical). (cont.)

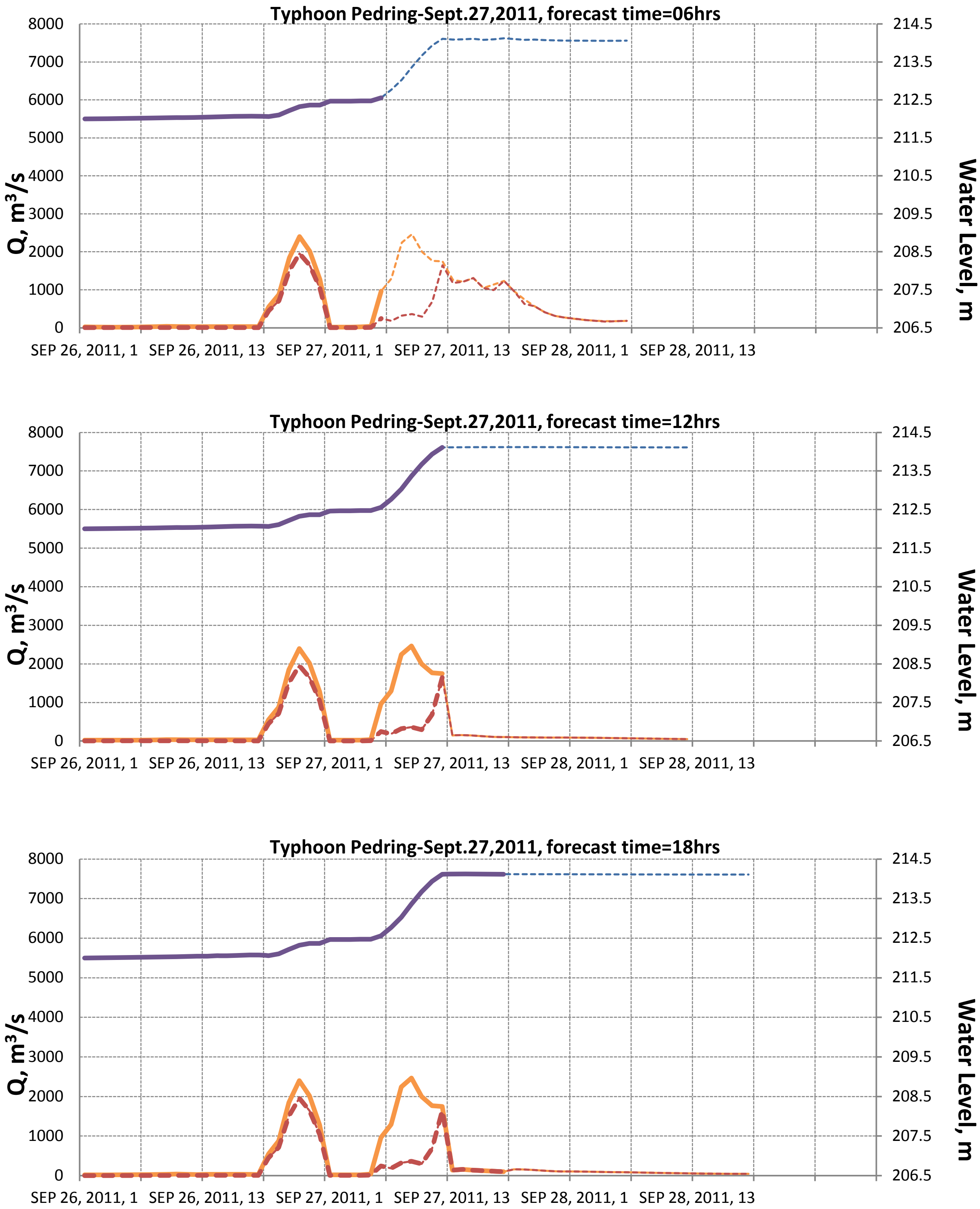


Figure 5.12-1. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 214m. Initial condition is increased from observed 207m to 212m (hypothetical).

Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps.

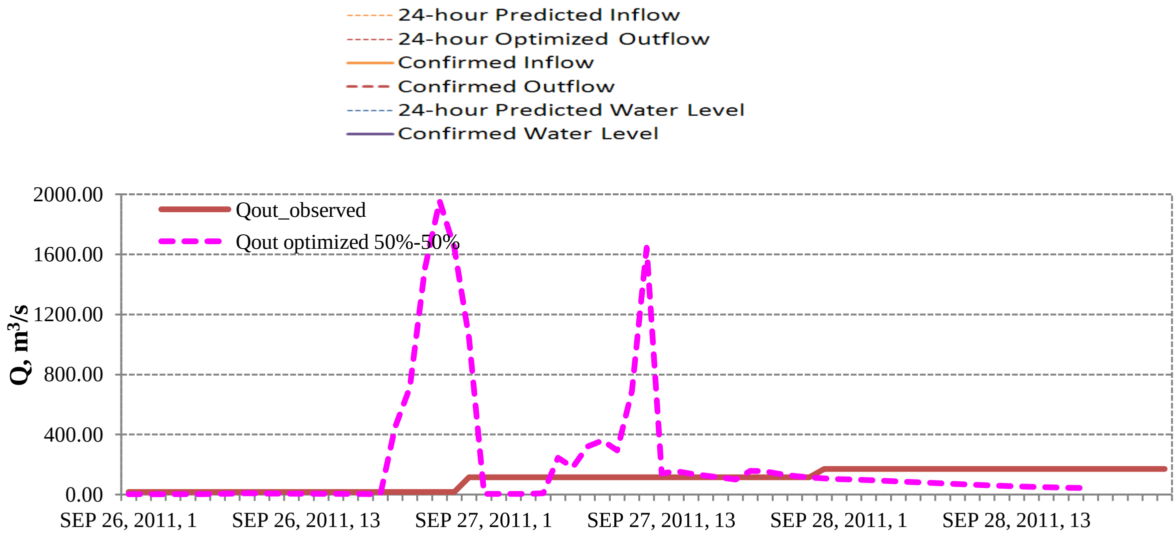


Figure 5.12-2. Typhoon Pedring 6-hourly average of dam release from daily observed and 50%-50% optimization scheme at initial water level changed from 207m to 212m.

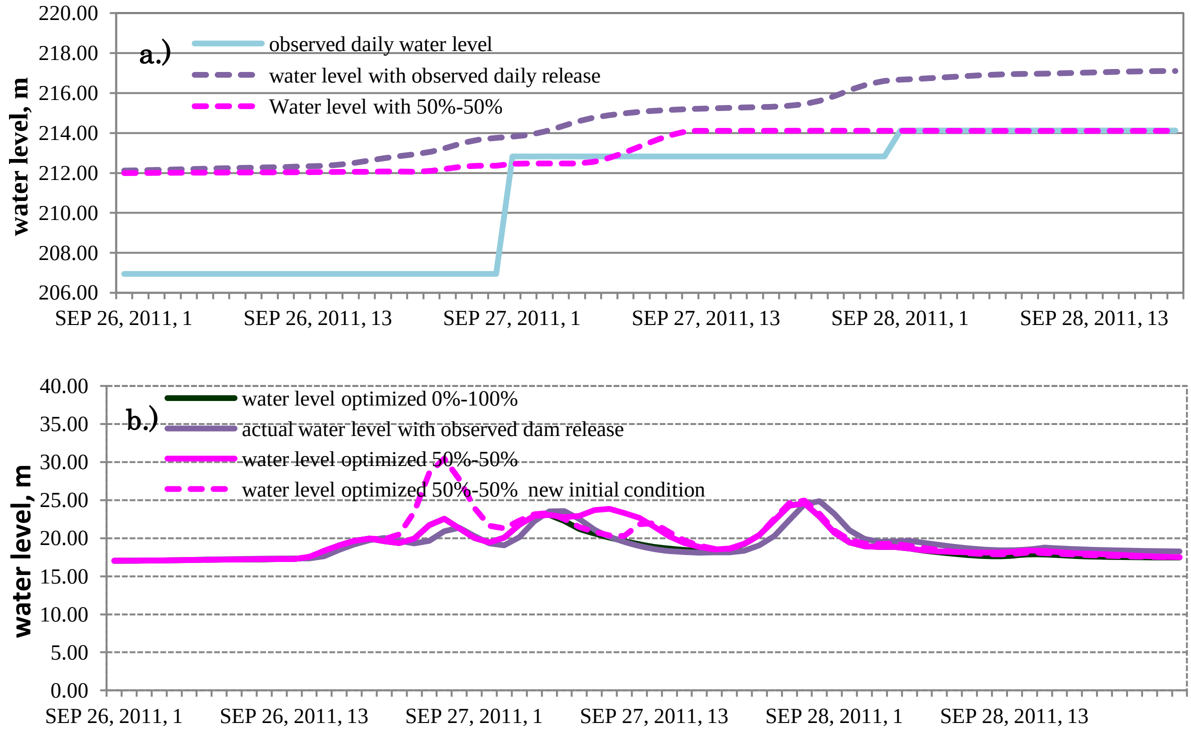


Figure 5.12-3. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)** downstream at 50%-50% optimization scheme at initial water level changed from 207m to 212m.

The dam releases using this new assumption of a higher water level is given in **Figure 5.12-2**. Note that compared to **Figure 5.11-7**, the dam releases for this new assumption is much higher. This is as a result of the reduced storage capacity of the dam as a result of having an initial higher water level. However, whatever the water level assumed, the optimization scheme is able to maintain the reservoir water level upstream (**Figure 5.12-3a**) to a level below the critical level 214m and the downstream (**Figure 5.12-3b**) water level (although close to critical) was maintained below the 33.3m limit.

5.13 Case Study 5: Typhoon Pedring at 212m Water Level Limit at 50%Priority on Flood-50% Priority on Water Storage

This last case assumes the same initial water level of 207m but changes the critical water level in the dam from 214m to 212m. The dam release from the 212m water level occurred on September 26th and on the latter part of September 27th while the dam release for the 214m water level occurred on the 27th. Varying the critical water level in the reservoir can actually affect the dam releases even if for the case of Pedring, setting the limit to 214m stores water to a maximum of about 212.7m only. This is why in Figure **5.13-2a**, the 50%-50% for the 212m and the 214m limits have almost the same final water levels. For the downstream water levels (at Matictic), the simulation with the 212m limit resulted to higher water levels on the 26th and 28th of September however these water levels are also both below the 33.3m limit.

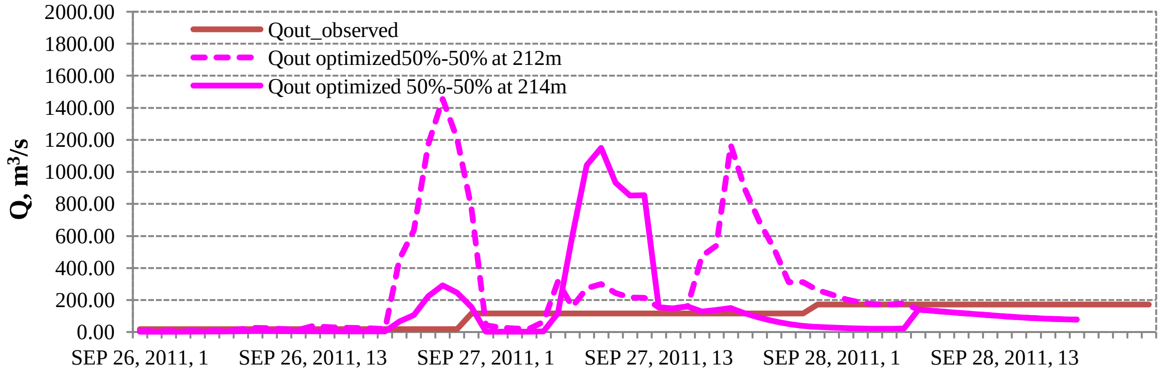


Figure 5.13-1. Typhoon Pedring 6-hourly average of dam release with different reservoir water level limits of 212m and 214m from 50%-50% optimization scheme.

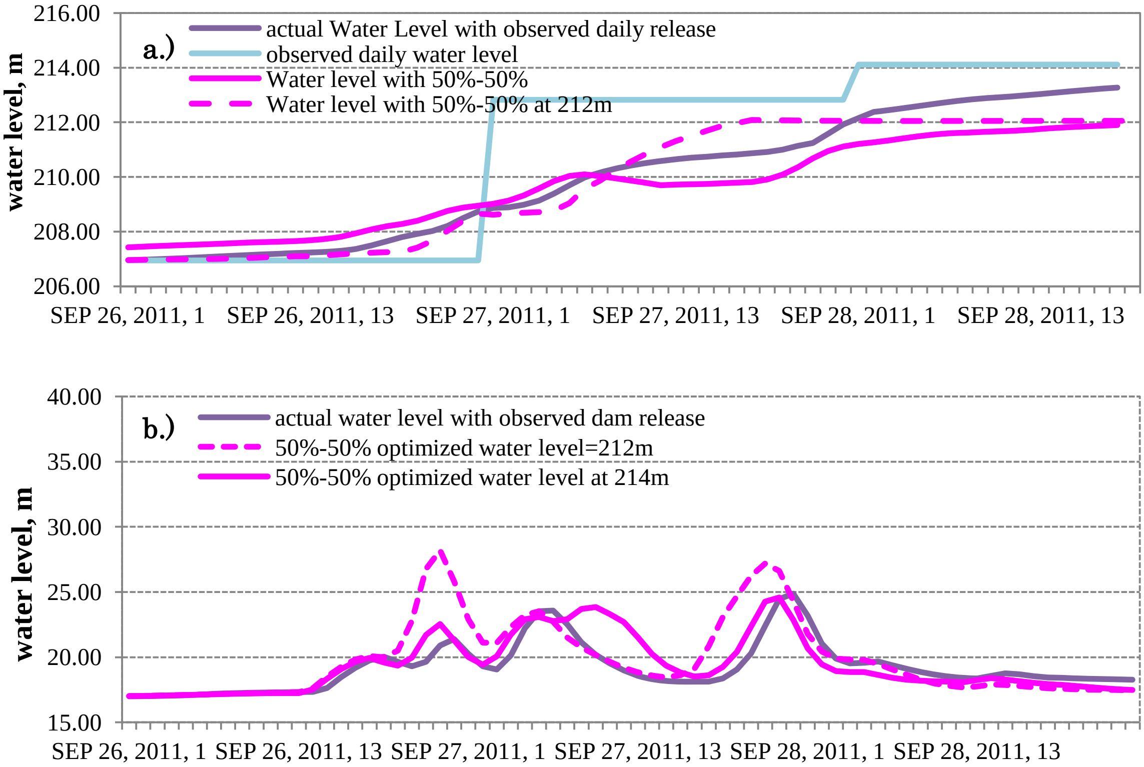
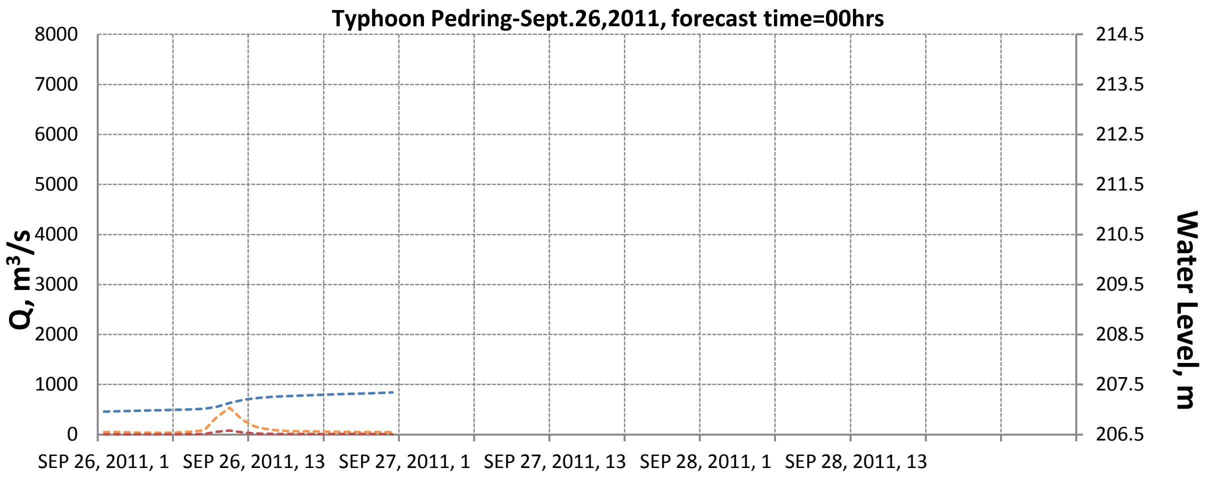
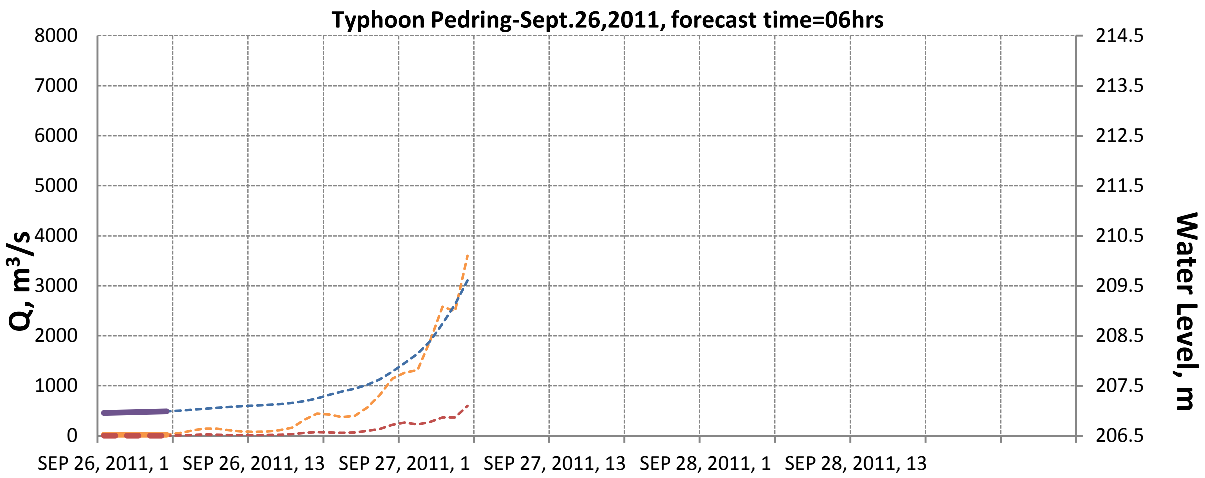


Figure 5.13-2. Typhoon Pedring 6-hourly average of water level from **a.)** upstream and **b.)**downstream for 50%-50% priority with different reservoir water level limits of 212m and 214m from 50%-50% optimization scheme.





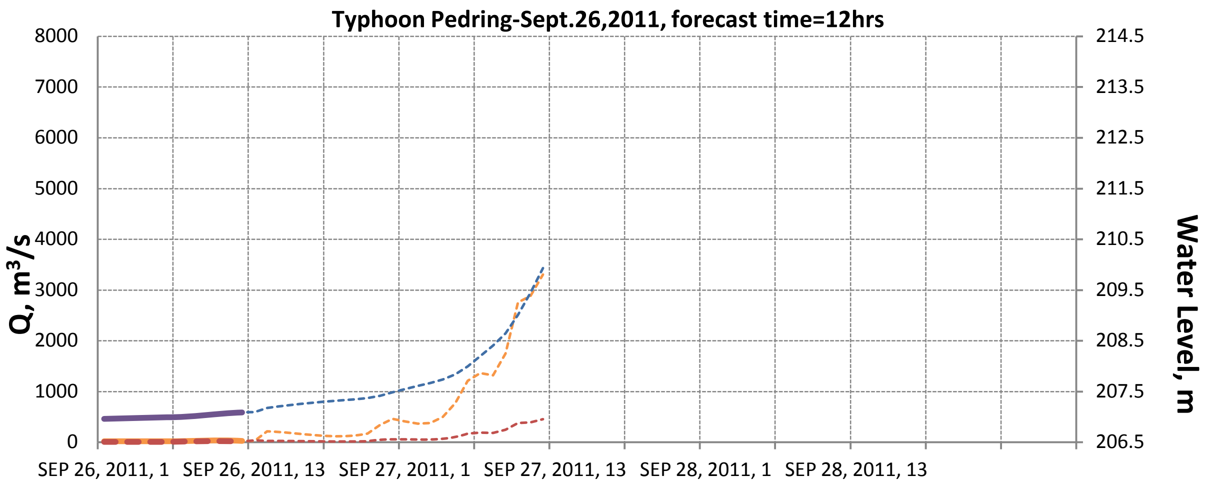


Figure 5.13-3. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 212m. (cont.)

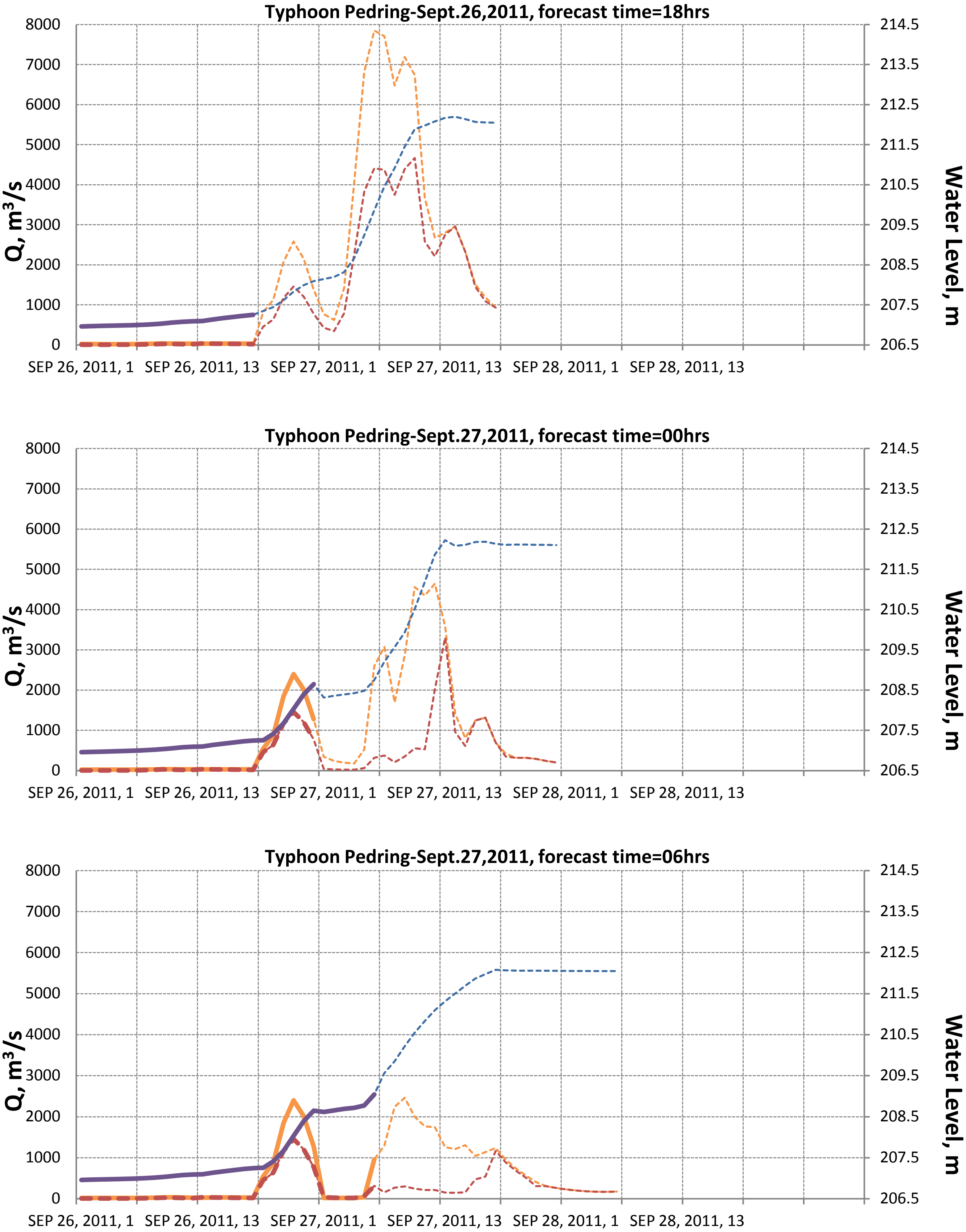
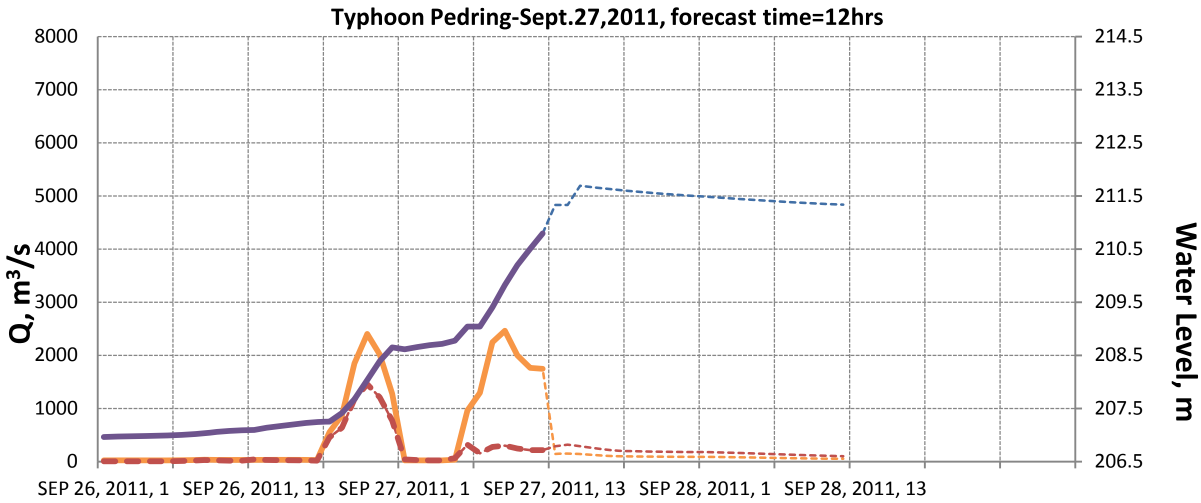


Figure 5.13-3. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 212m. (cont.)



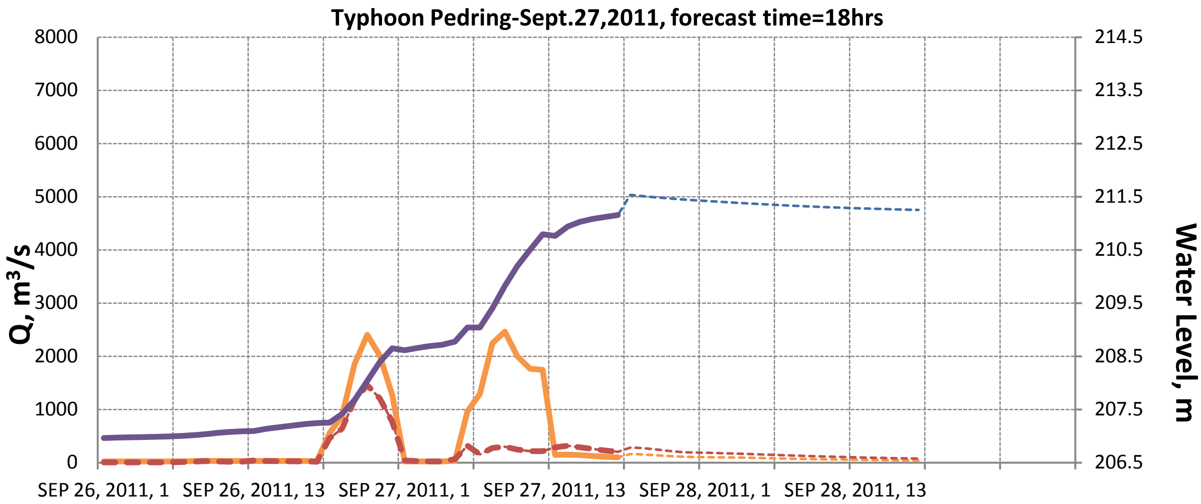
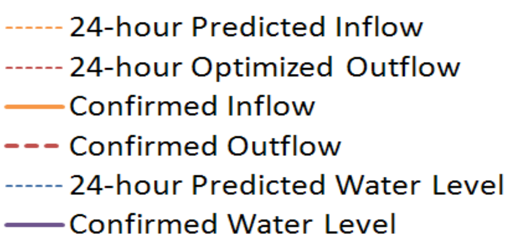


Figure 5.13-3. Forecast water level (blue), dam inflow (orange) and optimized outflow (red) for typhoon Pedring with 50% priority of water storage and 50% priority on flooding downstream with dam reservoir maximum limit at 212m.

Broken line shows 24 hours forecast; solid line shows simulated average for the previous time steps [see legend below].



CHAPTER 6 Conclusions and Recommendations

This study presents the following conclusions:

1) To contribute to the water budget study in Angat, Kaliwa and Pampanga River basins, river discharge datasets in past and future were completed by considering the impacts of climate change. After the selection of appropriate GCMs from 24 models in the SRESA1b scenario, this study carries out the bias correction and downscaling of projected rainfall by the GCMs and then assesses the impacts of climate change on floods and droughts. Based on results from the 3 basins, it is virtually certain that larger floods will occur more often in the future as shown in **Figure 4.2-2, 4.3-2, and Figure 4.4-2**. On the other hand, the results also suggested that severe droughts will very likely occur in the Pampanga river basin as shown in **Table 4.4-1**, but about as likely as not in Angat and Kaliwa, in **Table 4.2-1** and **Table 4.3-1**.

2) This study also introduces an ensemble forecast system, based on forecast error evaluation from previous quantitative precipitation forecast (QPF) issued by PAGASA, for the sake of appropriate dam operation. It suggests that this ensemble method might be also applicable into optimization of dam operation for reducing flood peaks and making maximum use of water. In this fashion, this study shows that optimization of dam operation is one of effective measures for adapting to climate change by showing **Figure 5.9-5.13**. In order to minimize floods at the control point and maximize reservoir storage, a combined objective function is set-up. 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 and replenish/increase the storage volumes. The results from three events indicate the system is feasible in real-life dam operation.

Based on above conclusions, this study recommends a project for prototyping a system for optimization of dam operation toward operational use through multi-stakeholder collaboration by putting high priorities on the following points:

i. *Capability of bias correction of radar rainfall*

   Quantitative information of spatially distributed rainfall as well as qualitative one is indispensable for getting reliable flood prediction by making maximum use of rainfall prediction.

ii. *Real-time data acquisition capability*

   To get the bias corrected radar rainfall, real-time rain gauge data collection system should be established. The weather prediction issued by PAGASA is also passed to the operating system in real-time basis.

iii. *Real-time system running capability*

A real-time data integration and analysis function should be developed. In addition, decision making support tools and data dissemination function are needed.

iv. *Design of priority and cost function including the Laiban Dam operation through discussion with decision makers*

"Optimization" should be defined by actual stakeholders. Priorities and cost functions can be suggested from off-line simulations by using the data integration and analysis through collaborative work between stakeholders and operational sectors.

v. *Operator training*

The prototyping system is requested to offer a function of training simulator. It is critically important to build capacity for effective and safe use of the system.

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