

RESEARCH ARTICLE

Angat Multipurpose Reservoir with Increased Water Demand and Future Reservoir Sedimentation

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Abstract: The Angat Reservoir is a multipurpose reservoir serving competing uses for Metro Manila's domestic water supply and Bulacan's Angat-Maasim River irrigation system with a privatized hydropower generation component. This study assesses the reliability of Angat Reservoir operations to deliver these demands with an increased domestic water supply requirement from 46 to 50 m³/sec and with future reservoir sedimentation in 2050. A reservoir optimization-simulation model is employed to simulate daily reservoir operations with long-term generated inflows from a watershed model. Then, the resulting daily reservoir releases for each scenario are subjected to flow duration analysis in the context of reliability analysis to assess the competing water uses of Angat Reservoir.

Keywords: Competing water uses, reservoir optimization-simulation, reliability analysis, reservoir sedimentation

JEL Classifications: C61, O21 and Q25

The Angat Reservoir is a multipurpose reservoir serving Metro Manila's domestic water supply needs under the Metropolitan Water Supply and Sewerage (MWSS) and Bulacan's irrigation demand for about 24,000 hectares of riceland in the Angat-Maasim River Irrigation System (AMRIS) under the National Irrigation Administration (NIA) including hydropower generation and flood control.

Competing Uses of Angat Reservoir by Its Physical Configuration and Water Rights

The Angat Reservoir system has essentially competing uses by virtue of its physical configuration and water rights allocation for the different water uses. As shown in Figure 1, the main hydropower plant (HP) generation with a capacity of 200 megawatts

(MW) is through releases to NIA for irrigation. The auxiliary HP generation with a capacity of 46 MW is through releases to MWSS for domestic water supply. However, twice as much power can be generated at the main HP compared with the auxiliary HP for the same flow discharge, since at, say, a reservoir elevation of 205 meters (m), the head for power generation for the main HP is 187.5 m (that is, 205–17.5 m tailwater elevation), while that for the auxiliary HP is 104 m (that is, 205–101 m tailwater elevation at Ipo Dam). However, NIA and MWSS water rights, originally, after Angat Dam was built in 1968, NIA had 36 m³/sec (CMS), while MWSS had 22 CMS, a total of 58 CMS, which is the amount equal to the water rights granted to the National Power Corporation to operate Angat Reservoir for its hydropower generation objectives provided that the MWSS (domestic water supply) and NIA (irrigation) water rights or allocations are satisfied on a long-term, average daily basis. The long-term average is emphasized here because NIA has seasonal water requirements in contrast to MWSS, which is fixed on a daily basis. Since 2000, with additional

water from the Umiray River transbasin transfer, the water rights situation has evolved into the following: (a) MWSS water rights became 46 CMS, which is the sum of the original 22 CMS plus 15 CMS referred to as conditional water rights from NIA plus nine CMS from the Umiray River; (b) NIA-AMRIS water rights were reduced to 21 CMS, which is the original 36 CMS minus 15 CMS; and (c) Bulacan bulk water rights are three CMS, which comes from the Umiray River transbasin transfer. The above water rights allocation is based on the long-term average inflow of the Angat and Umiray watersheds of 70 CMS.

In view of the above change in water allocation and priority, 200 MW capacity of the main HP of Angat is seldom reached, since NIA’s allocation has been reduced to 21 CMS from its original 36 CMS. Also, in accordance with the Philippine Water Code, during water shortage conditions, the order of priority of water delivery from a multipurpose reservoir like Angat is to first satisfy domestic supply, followed by irrigation demand and hydropower that is incidentally generated.

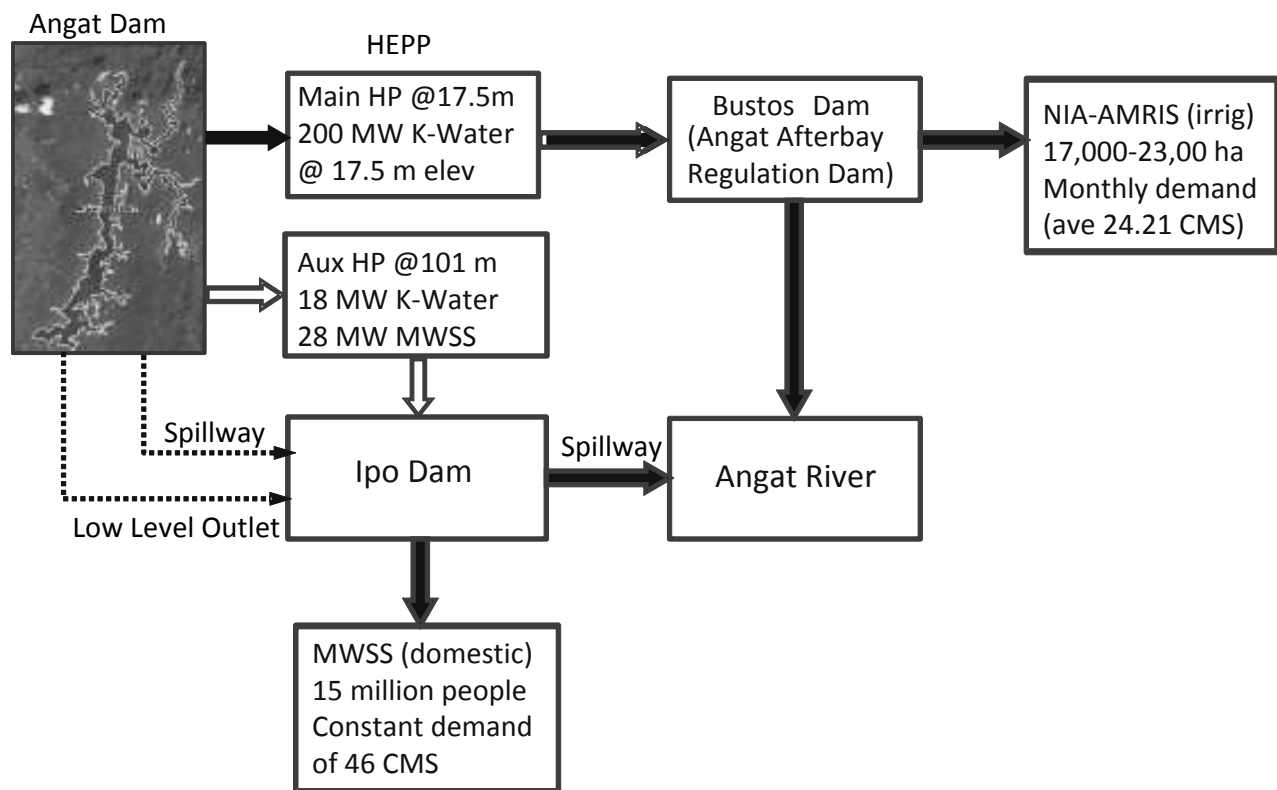


Figure 1. Physical components and water demands of the multipurpose Angat Multipurpose Reservoir System for domestic water supply, irrigation water supply, hydropower generation and flood control.

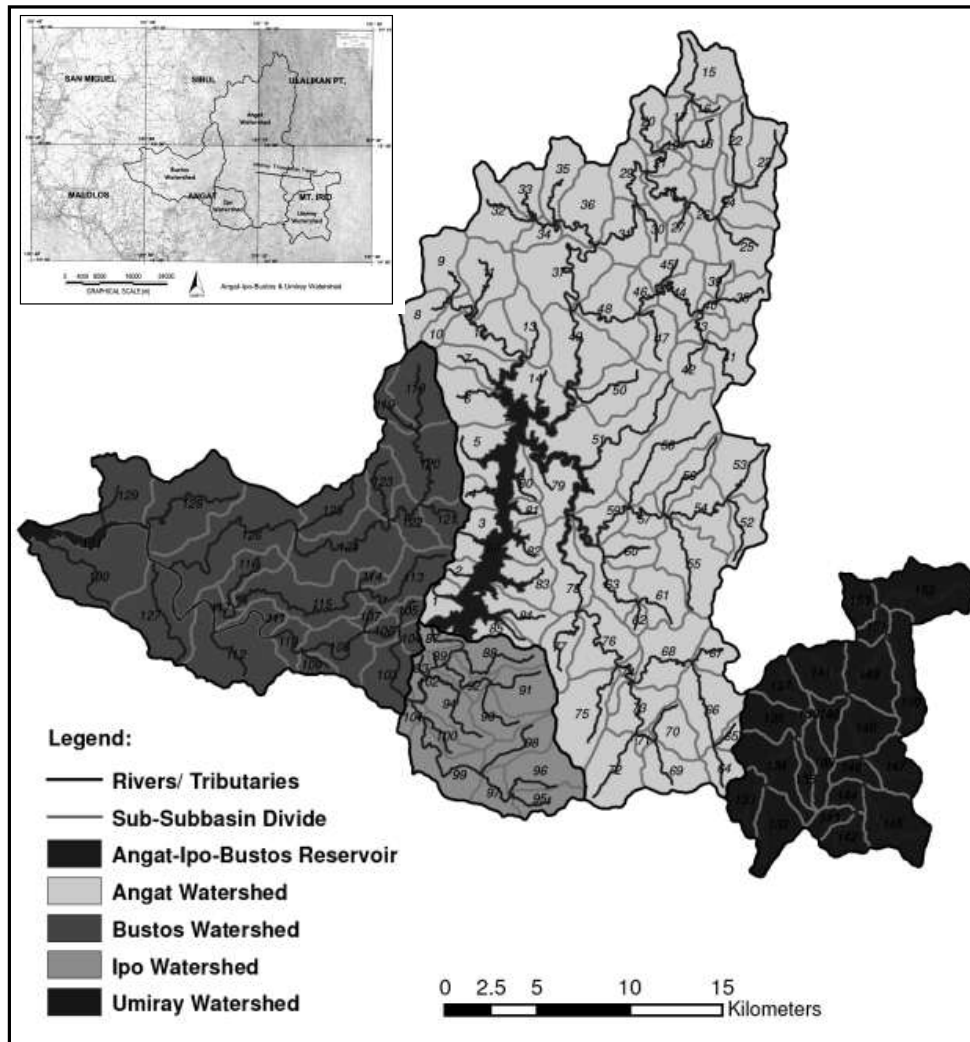


Figure 2. Watershed delineation and river network of the Angat-Ipo-Bustos-Umiray water resources system.

Angat Optimization-Simulation Model with Watershed Model

Figure 2 shows the Angat Reservoir system with the Angat, Ipo, and Bustos watersheds and river network. For purposes of watershed modeling, the watershed system is delineated into 153 sub-basins according to basin topography, river network configuration, and slopes—considering as well the geology, soil types, vegetation, and land use. The watershed model employed in this study is a continuous-time, distributed model consisting of various components: rainfall input, evaporation, surface detention, infiltration, overland flow, channel flow, and, most importantly, the Sacramento soil-moisture accounting model. For each sub-basin (see Figure 2) composed of two overland

flow planes, the hourly evolution of soil-moisture with or without rainfall results in overland and channel flows that are routed in each overland flow plane and into the channel or stream network of the basin from upstream to downstream. The daily rainfall record available in this study is from January 1974 to December 2012 for a total of 38 years of daily flows that can be generated from the watershed model to conduct Angat Reservoir operations and a reliability study.

The WATPOW model originally developed by Tabios and Shen (1993) is used in the optimization-simulation study of the Angat-Ipo-Bustos-Umiray water system. The model consists of a simulation module to represent the physical processes involved in reservoir operations and an optimization module to specify the reservoir operating policies such as

release schedules. The model geometry is defined by a node-link network representation of the Angat-Ipo-Bustos Reservoir system as shown in Figure 1 where the inflow points (as links) are the Angat River and Umiray River; local inflows between the reservoirs Angat and Ipo and, Angat and Bustos; the Angat Dam, Ipo Dam, and Bustos Dam as reservoir nodes; Main and Auxiliary hydropower plants (as nodes); and the links to the demands nodes, NIA-AMRIS irrigation system of Bulacan and MWSS of Metro Manila.

The objective function of the optimization-simulation model is a weighted multi-objective to minimize water supply deficits (demand violations), maximize hydropower generation, and minimize spills. The constraints include capacities of release gates, storage volumes, operational constraints, and all other system constraints imposed implicitly in the simulation model. Specifically, the objective function to be maximized is given by

$$F = p_{WS} \min(QWS_t - QWD_t, 0.0) + p_{IR} \min(QIR_t - QID_t, 0.0) - p_{SP} QSP_t + b_M EM_t + b_A EA_t \quad (1)$$

where QWS_t and QWD_t are MWSS water supply release (through the auxiliary HP) and MWSS water demand, respectively, at time t with penalty coefficient p_{WS} ; QIR_t and QID_t are the NIA-AMRIS irrigation release (through main HP) and irrigation demand, respectively, with penalty coefficient p_{IR} ; QSP_t is the reservoir spill with penalty coefficient p_{SP} ; EM_t is the energy generated at the main HP with benefit coefficient b_M ; and EA_t is the energy generated at the auxiliary HP. In the optimization algorithm, the foresight or hedging into future flow conditions is accounted for through a 30-day *moving planning horizon* so that the next day's reservoir releases are based on the summation of F in Equation (1) for the next 30 days. This scheme is also referred to as anticipatory release policy as done in Tabios (2008).

The major constraint function imposed in the Angat Reservoir operation study is the hard system constraint described by the reservoir water balance computations, maximum flow capacities of controlled releases, and the flood control storage requirement. Note that the water supply and irrigation demand violations, as well as spillway flows, are imposed as soft constraints incorporated in the objective function as penalty functions.

Optimization-Simulation Model Scenarios

The optimization-simulation studies were conducted for three (3) scenarios described in detail below: (a) existing case or conditions with 46 CMS MWSS demand; (b) with increased MWSS demand from 46 to 50 CMS; and, (c) with future reservoir sedimentation in 2050 with 46 CMS MWSS demand

Scenario with Existing MWSS Demand at 46 CMS

This optimization-simulation scenario is for the existing or current water demands (on a daily basis) from Angat Reservoir. In particular, the MWSS domestic water supply demand is 46 CMS, while the NIA-AMRIS irrigation water demand varies from month-to-month.

Scenario with Increased MWSS Demand at 50 CMS

This scenario is the same as the existing case but with increased MWSS domestic water supply demand from 46 to 50 CMS.

Scenario with Reservoir Sedimentation in 2050

This scenario is to assess the reliability of the Angat Reservoir system to deliver water to MWSS and NIA-AMRIS with future sediment deposition in Angat Reservoir around 2050. The future sediment scenario was created based on the historical reservoir sediment accumulated or deposited in Angat Reservoir, estimated to be about 4.128 million cubic meters (MCM) per year. This was computed from the difference between the original reservoir volume of 1,050 MCM in 1967 at 217 m reservoir elevation and the current volume of about 855 MCM (in 2013), also at 217 m reservoir elevation. Assuming the same sediment inflow rate in the future, the reservoir volume at 217 m elevation will be about 702 MCM in 2050, which is a total of 153 MCM reservoir sediment deposited by 2050 from 2013. The future reservoir sediment deposition scenario is accounted for in the optimization-simulation model with the 2050 reservoir storage-elevation curve as shown in Figure 3. Also shown in this figure is the current storage-elevation curve. This future sediment scenario storage-elevation curve assumes that the sediment deposition is uniformly deposited in the reservoir at the ratio 0.82 (from the quotient of 702/855).

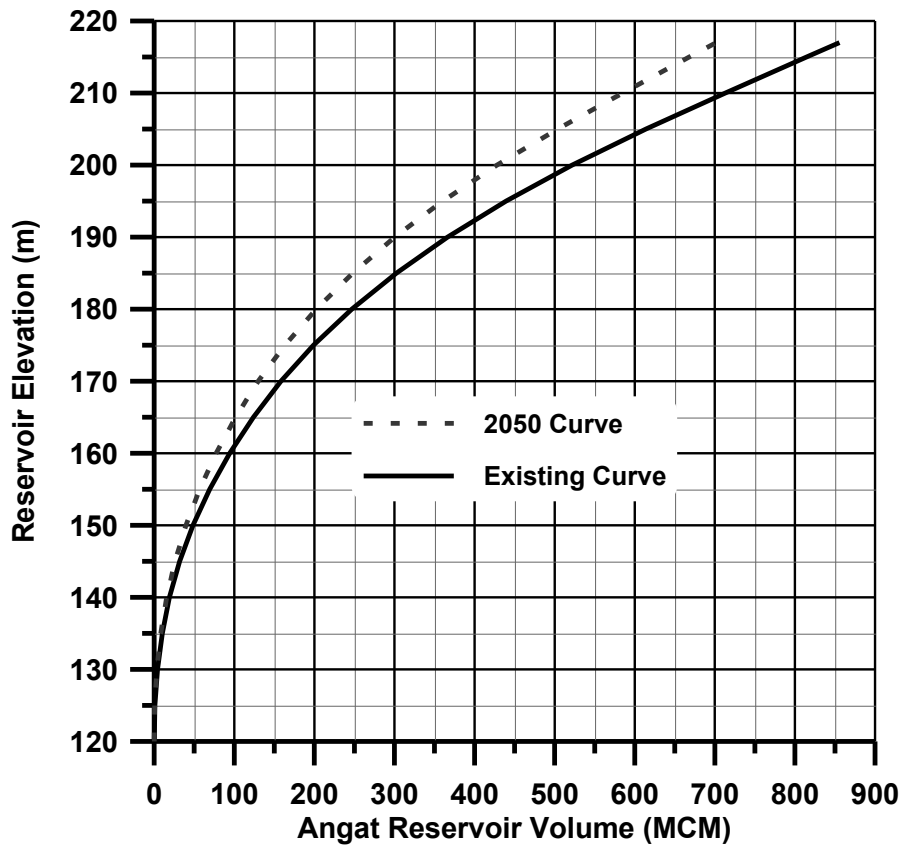


Figure 3. Angat Reservoir elevation-volume curves for existing case (circa 2013) and with reservoir sediment deposition in 2050.

Results of Optimization-Simulation Studies

In the optimization-simulation studies, the coefficients in the objective function in Equation (1) were first determined to arrive at some reasonable values to reflect the fact that domestic water supply has priority over irrigation water supply. With 38 years of daily streamflow generated (January 1974 to December 2012) from the watershed model, the optimization-simulation model runs were conducted to determine the reservoir releases and associated hydropower generation. Then the flow duration curves (as the basis of reliability analysis) were calculated on a monthly basis by pooling all the daily reservoir releases and hydropower generated by month. For all three optimization-simulation scenarios, the flow duration curves are given in Table 1 for Angat Reservoir releases to Ipo Dam and Bustos Dam, respectively, while Table

2 shows the power duration curves for the auxiliary and main hydropower plants (HPs), respectively. Note that HP generations are based on 10 hours a day of operation, so that the power generated (in MW) may be more than the actual installed capacities of these plants.

Comparing the results of scenario (a) (with 46 CMS MWSS demand) and scenario (b) (with 50 CMS MWSS demand), generally, at higher MWSS water demand, the reliability (in terms of percent-of-time water deliveries) of the NIA-AMRIS water releases is lower. This is expected, since the MWSS water deliveries are given priority, especially during dry-year periods, when the Angat Reservoir elevations go below 180 m. At 46 CMS MWSS water demand, the reliability of water deliveries is 80 percent-of-time for the months of January and June through December, but only 60 percent-of-time during the dry months

Table 1. *Angat Reservoir Daily Releases to Ipo Dam for MWSS Domestic Water Supply for Three (3) Optimization-Simulation Scenarios*

Month	Percent of Time	Angat Reservoir Releases (CMS)					
		Releases to Ipo Dam			Releases to Bustos Dam		
		46 CMS MWSS Demand	50 CMS MWSS Demand	Future Reservoir Sedimentation	46 CMS MWSS Demand	50 CMS MWSS Demand	Future Reservoir Sedimentation
Jan	80	46.00	47.36	4.59	36.00	34.42	0.00
	60	46.00	50.00	9.79	36.00	36.00	0.00
	40	46.00	50.00	19.13	45.98	49.85	0.00
Feb	80	29.77	23.79	3.37	27.49	20.50	0.00
	60	46.00	47.72	5.79	39.82	34.97	0.00
	40	46.00	50.00	10.78	39.86	39.86	0.00
Mar	80	5.70	3.79	3.06	1.31	0.08	0.00
	60	36.70	30.51	5.26	22.07	15.50	0.00
	40	46.00	50.00	9.74	31.00	31.00	0.00
Apr	80	4.09	3.74	3.67	0.00	0.00	0.00
	60	19.43	12.80	7.09	0.00	0.00	0.00
	40	46.00	50.00	15.50	15.50	15.50	0.00
May	80	14.38	13.49	8.41	0.00	0.00	0.00
	60	46.00	50.00	23.85	0.00	0.00	0.00
	40	46.00	50.00	46.00	0.00	0.00	0.00
Jun	80	46.00	50.00	27.29	27.90	27.90	0.00
	60	46.00	50.00	46.00	27.90	27.90	5.57
	40	46.00	50.00	46.00	27.90	27.90	27.90
July	80	46.00	50.00	43.32	28.00	28.00	0.00
	60	46.00	50.00	46.00	28.00	28.00	25.00
	40	46.00	50.00	46.00	28.00	28.00	28.00
Aug	80	46.00	50.00	44.30	25.00	25.00	0.00
	60	46.00	50.00	46.00	25.00	25.00	22.73
	40	46.00	50.00	46.00	25.00	25.00	25.00
Sep	80	46.00	50.00	38.06	22.73	22.73	0.00
	60	46.00	50.00	46.00	22.73	22.73	13.00
	40	46.00	50.00	46.00	22.73	22.73	22.73
Oct	80	46.00	50.00	23.32	13.00	13.00	0.00
	60	46.00	50.00	45.76	13.00	13.00	0.81
	40	46.00	50.00	46.00	13.00	13.00	13.00
Nov	80	46.00	50.00	13.52	17.57	17.57	0.00
	60	46.00	50.00	29.94	17.57	17.57	0.00
	40	46.00	50.00	46.00	17.57	17.57	15.96
Dec	80	46.00	50.00	9.32	36.00	36.00	0.00
	60	46.00	50.00	19.79	36.00	36.00	0.00
	40	46.00	50.00	46.00	45.99	49.99	10.60

Note: The three scenarios are (a) with 46 CMS MWSS demand; (b) with 50 CMS MWSS demand; (c) with reservoir sedimentation with 46 CMS demand. Irrigation demand is same for all scenarios. (Written in italic bold are cases that did not meet water demand).

of February through May. At 60 percent-of-time, it can be expected that the reservoir release to MWSS (through Ipo Dam) is greater than or equal to 46 CMS, 220 days a year, on the average and in the long term. At 50 CMS MWSS water demand, the reliability generally becomes lower, but with only a relatively

small decrease compared with the existing case with 46 CMS MWSS water demand, especially during the dry months of February to May, which is only expected with the 5.0 CMS increase in MWSS water demand. It may be mentioned that the 46 CMS, as natural Angat River flows at the Angat Reservoir dam site (assuming

Table 2. Auxiliary and Main Hydropower Plant Generations from Angat Reservoir Daily Flow Releases for the Three (3) Optimization-Simulation Model Scenarios

Month	Percent of Time	Angat Main Hydropower Generation (MW)					
		Auxiliary Hydropower Plant			Main Hydropower Plant		
		46 CMS MWSS Demand	50 CMS MWSS Demand	Future Reservoir Sedimentation	46 CMS MWSS Demand	50 CMS MWSS Demand	Future Reservoir Sedimentation
Jan	80	81.77	75.28	5.68	129.98	116.44	0.00
	60	91.79	95.21	12.11	146.78	140.71	0.00
	40	101.56	107.51	24.06	169.36	178.04	0.00
Feb	80	43.31	32.59	4.17	89.13	65.42	0.00
	60	79.17	74.44	7.17	137.13	117.75	0.00
	40	94.55	97.79	13.38	158.87	152.89	0.00
Mar	80	7.05	4.69	3.78	3.95	0.25	0.00
	60	50.89	40.21	6.51	70.04	50.85	0.00
	40	84.51	86.96	12.08	112.89	105.78	0.00
Apr	80	5.06	4.63	4.54	0.00	0.00	0.00
	60	24.04	15.84	8.77	0.00	0.00	0.00
	40	71.52	69.76	19.18	55.29	52.65	0.00
May	80	17.79	16.70	10.41	0.00	0.00	0.00
	60	58.31	62.58	29.51	0.00	0.00	0.00
	40	68.17	68.51	112.38	0.00	0.00	0.00
Jun	80	60.09	63.22	34.24	86.25	84.86	0.00
	60	68.52	70.26	56.92	93.41	89.17	16.78
	40	76.61	77.53	112.38	102.36	95.39	117.73
July	80	64.91	67.07	53.87	89.00	86.73	0.00
	60	76.76	79.61	112.38	100.26	96.28	105.49
	40	86.33	89.56	112.38	109.21	103.96	118.15
Aug	80	82.21	85.81	55.01	89.29	87.33	0.00
	60	89.55	93.88	112.38	94.11	92.18	95.91
	40	95.46	100.53	112.38	99.88	96.77	105.49
Sep	80	90.72	93.48	47.30	84.47	82.13	0.00
	60	95.69	100.12	56.92	88.06	86.69	54.24
	40	103.18	108.37	112.38	92.59	92.15	95.91
Oct	80	94.44	98.57	28.86	50.26	49.12	0.00
	60	101.26	105.60	56.91	52.54	51.64	2.43
	40	106.39	111.69	112.38	54.78	54.78	54.85
Nov	80	95.43	99.75	16.81	69.94	67.96	0.00
	60	103.40	108.13	37.38	73.47	72.27	0.00
	40	109.57	116.61	56.92	74.14	74.14	48.51
Dec	80	91.90	94.81	11.53	141.77	136.67	0.00
	60	100.12	105.31	24.67	151.74	148.81	0.00
	40	106.75	114.02	56.92	178.57	186.47	31.95

Note: Written in italic bold are cases that are below the long-term, monthly firm power ratings for the hydropower plants.

no reservoir), is only about 40 percent-of-time such that the natural river flows can be expected only to be equal to or greater than 46 CMS about 146 days a year. Obviously, the value of having the Angat Reservoir is to increase the reliability of the water availability for a particular water demand.

With future sediment deposition (scenario (c) with MWSS demand of 46 CMS), the ability of the Angat Reservoir to deliver the water demand is already compromised compared with the other scenarios. In fact, there are practically no irrigation water deliveries (through Bustos Dam) during the months of December

through May and subsequently no power generation at the main HP. Thus, future reservoir sediment deposition can significantly compromise the ability of the Angat Reservoir to deliver water for domestic and irrigation purposes as well as hydropower generation. Proper and serious watershed protection and sediment yield control measures should be employed in the Angat River basin to preserve or prolong the life of the Angat Reservoir.

Conclusions

On results of the optimization-simulation studies, generally, without future reservoir sedimentation, the Angat-Ipo-Bustos-Umiray water resources system can deliver the imposed water demands for MWSS and NIA-AMRIS with a reliability of about 80 percent-of-time during the months of June to December, but not quite during the months of February to May. With 80 percent reliability at 46 CMS MWSS water demand, it can be expected that the reservoir releases to MWSS will be equal to or greater than 46 CMS, 300 days a year, on the average. Note that the flow of 46 CMS in the Angat River at the Angat Reservoir dam site (assuming no reservoir) occurs only 40 percent-of-time such that natural river flows can be expected to be only equal to or greater than 46 CMS for 146 days a year. Obviously, the value of having the Angat Reservoir is to increase the reliability of the water available for extraction at a particular water demand.

With the future sediment deposition scenario, the optimization-simulation studies showed that the ability of the Angat Reservoir to deliver the water demand is drastically reduced over the months of October to May, which covers more than half of the year. Thus, future reservoir sedimentation can significantly compromise the ability of Angat Reservoir to deliver future domestic and irrigation water needs, so serious watershed protection and sediment yield control measures must be employed in the Angat River basin

in order to preserve and prolong the useful life of the Angat Reservoir.

Finally, the competing water uses of the Angat Reservoir for domestic water supply and irrigation demand is by virtue of its physical configuration of the system and also changes in water allocation and prioritization of domestic water supply over irrigation water supply in recent years. This has subsequently compromised hydropower generation in the main hydropower plant (with installed capacity of 200 MW), which may be unfavorable to the recent privatization of the hydropower asset. On the other hand, irrigation water demand has actually been reduced due to urbanization (conversion of rice fields to residential/commercial lands) as well as the seasonal flooding in the NIA-AMRIS area, thus leading to the transfer of 15 CMS of conditional water rights from NIA to MWSS due to unused NIA water rights (demand). In the case of Metro Manila's increasing domestic water demand, there is the need to look for an alternative water source for water security and redundancy since the Angat Reservoir can only supply so much.

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