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RESEARCH ARTICLE

Reliability and Cost-Benefit Analyses of the Balog-Balog Multipurpose Dam Versus Balog-Balog Multiple Dam Project

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Abstract: This study is to compare the Balog-Balog multipurpose, single dam project with the proposed Balog-Balog multiple dam system, using reliability and cost-benefit analyses, of the ability of the two reservoir systems to deliver irrigation water supply to the Balog-Balog irrigation system including hydropower generation and flood control functions through optimization-simulation model studies. On the basis of reliability to deliver irrigation water, generate hydropower, reservoir life, people displaced due to reservoir construction, flood control benefits, and economic analysis, the Balog-Balog single, high dam is better project compared to the multiple dam system.

Keywords: multipurpose reservoir, optimization-simulation, reliability analyses, cost-benefit analyses

JEL Classifications: Q15, Q25, C25, O22, H43

The Balog-Balog Irrigation System, as shown in Figure 1, consists of Phase I which covers irrigation service area of 12,475 ha while Phase 2 covers an area of 21,935 ha, thus a total area of 34,410 ha. Historically, in 1976, the irrigated area reached 12,904 ha, which was reduced to about 10,000 ha in 1989 but drastically reduced to less than 1,000 ha after the Mt. Pinatubo eruption in 1991. It has gradually recovered over the years to as high as 4,600 ha annual irrigated area. To fully rehabilitate the Balog-Balog Irrigation System, the National Irrigation Administration (NIA) proposed the construction of Balog-Balog Multipurpose Dam Project (BBMP), which has a single dam as the source of irrigation water. In 2012, a joint venture company, through an unsolicited proposal, proposed the Balog-Balog multiple dam system (BBMDS) which consists of series or cascade of nine low dams in the Bulsa River and O'Donnell River watersheds as an alternative to a single high dam (BBMP) proposed by NIA.

The main objective of this study is to compare the two proposed BBMP and BBMDS as two alternative components of the Balog-Balog irrigation system. The comparison is based on reliability analysis of the ability of these proposed reservoir systems to deliver irrigation water supply and possible hydropower generation, reservoir life due to sedimentation, flood control

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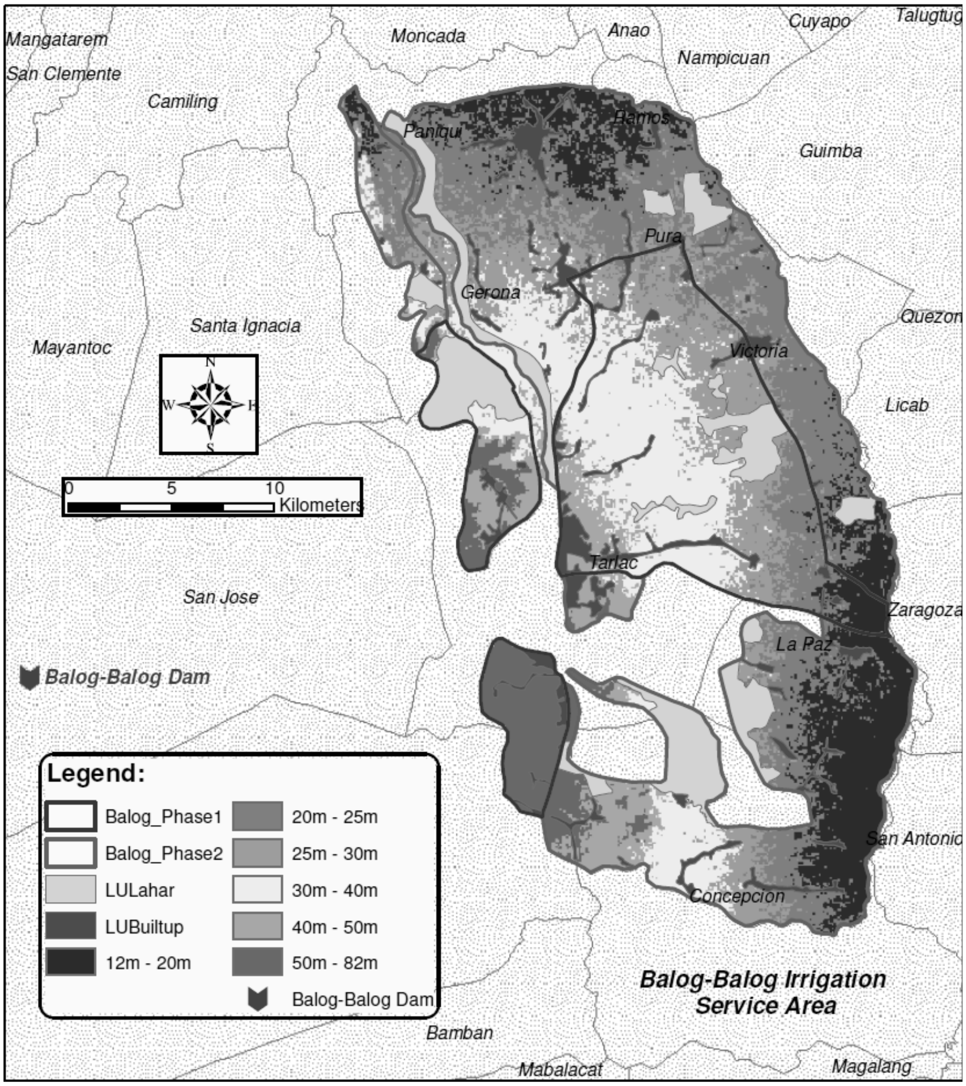


Figure 1. Map of Balog-Balog irrigation system.

benefits and economic analysis in terms of benefit-cost (B/C) analysis and internal rate of return (EIRR).

Optimization-Simulation Model

For purposes of reliability analysis, an optimization-simulation model is used to simulate the watershed/reservoir operations in which the watershed model represents the physical processes involved in the watershed system and reservoir operations and an optimization model is to decide the operating policies such as flow releases for specified objectives and constraints.

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. The heart of this model is the Sacramento soil-moisture accounting. The watershed model essentially calculates the daily streamflows as inflows to the reservoirs given the long-term, historical daily rainfall data from gaging stations around the study area. Figure 2 shows the O'Donnell-Tarlac watershed delineated into 57 sub-basins and also indicated are the locations of the reservoirs. There are 28 sub-basins that are associated to the proposed BBMDS while only 21 sub-basins are associated to BBMP. The spatial variability of rainfall is accounted for in the model by spatially interpolating point rainfall at the gaging stations for each sub-basin in the watershed.

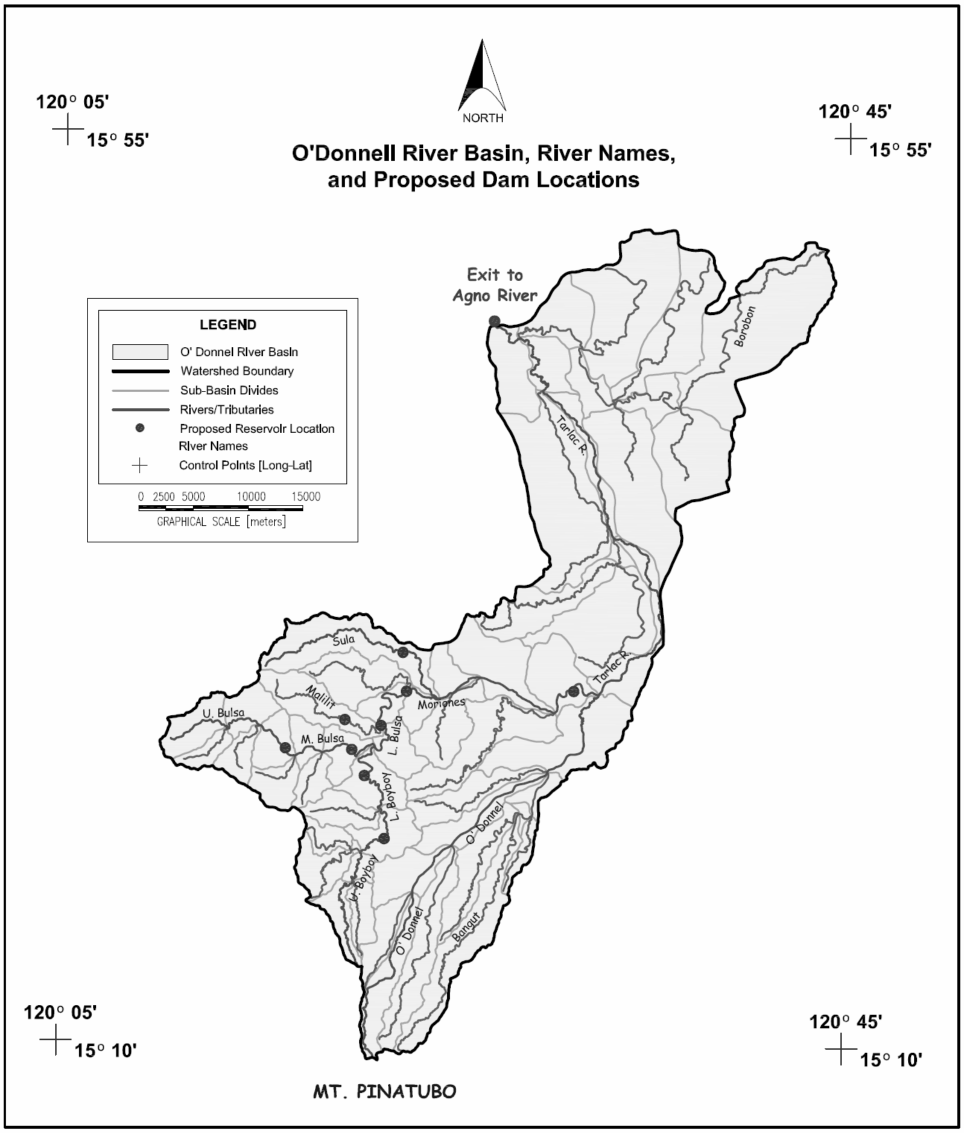


Figure 2. Map of the study area showing the watershed delineation and the locations of the proposed reservoirs.

In the optimization model, the complex nonlinear optimization method (Box, 1965) is used with a surrogate-worth, multi-objective function to minimize irrigation 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.

Balog-Balog Multipurpose, Single Dam Project (BBMP)

The BBMP has been the subject of several studies by NIA Consult, Inc. (2010, 2011, & 2012) and has been proposed by NIA as the major, alternative source of water for the Balog-Balog irrigation system. This is especially due to the closure of Armenia Dam at O' Donnell River and Tarlac Diversion Dam at Tarlac River, which were buried by lahar after Mt. Pinatubo's eruption in 1991. The Armenia Dam serves the irrigation areas of San Miguel-O’Donnell River Irrigation System (SMORIS) while the Tarlac Diversion Dam serves the irrigation areas of Tarlac River Irrigation System (TARRIS), which both composed the Balog-Balog Irrigation System.

Figure 3 shows the location of NIA’s proposed BBMP, which has locational coordinates 15^{0}25’54” latitude and 120^{0}21’13” longitude, slightly upstream of point S1 as indicated in this figure. The major data required in the reliability analysis is the reservoir elevation-storage-area curve, which is also shown in Figure 3. This curve was derived using SRTM digital terrain data with 90m x 90m spatial resolution. For purposes of the optimization-simulation model, the major reservoir and dam specifications are: 1) dam height is 95 m with base elevation at 150 m; 2)

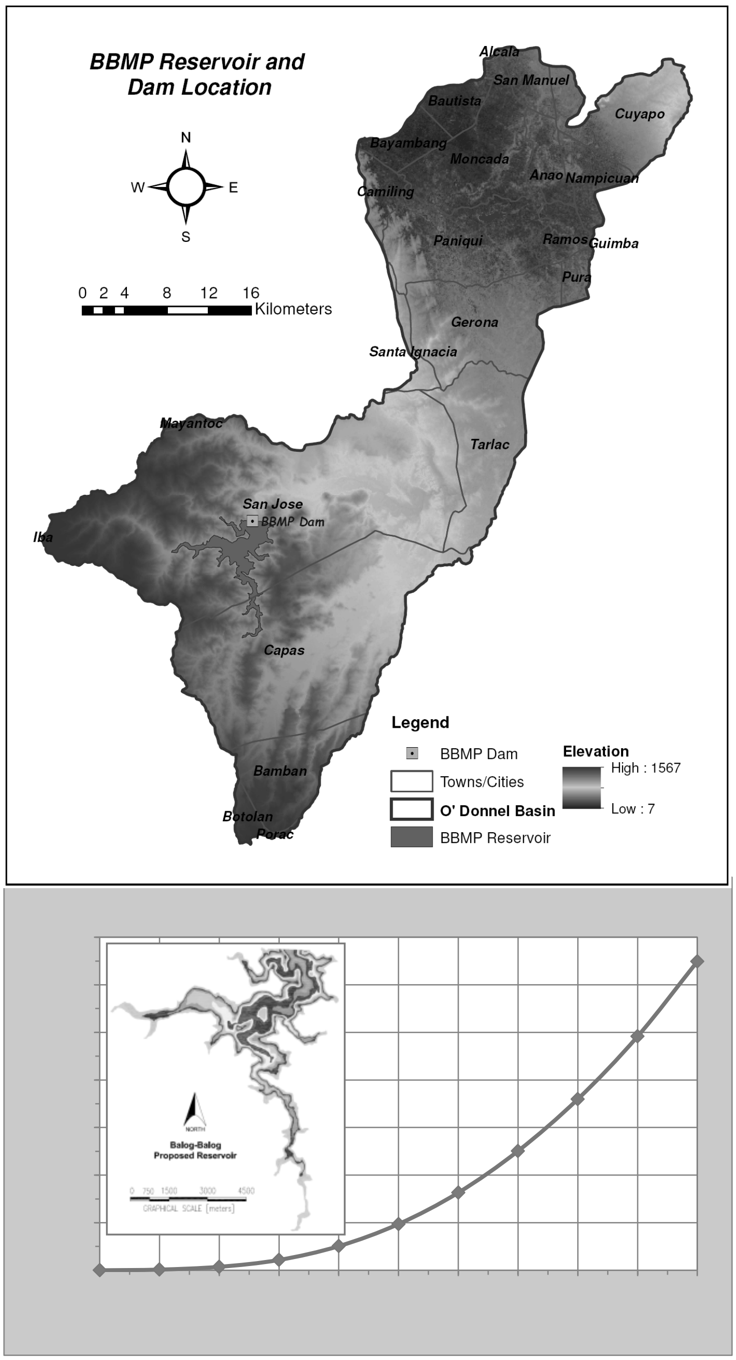


Figure 3. Location of BBMP and reservoir elevation-area-storage curve.

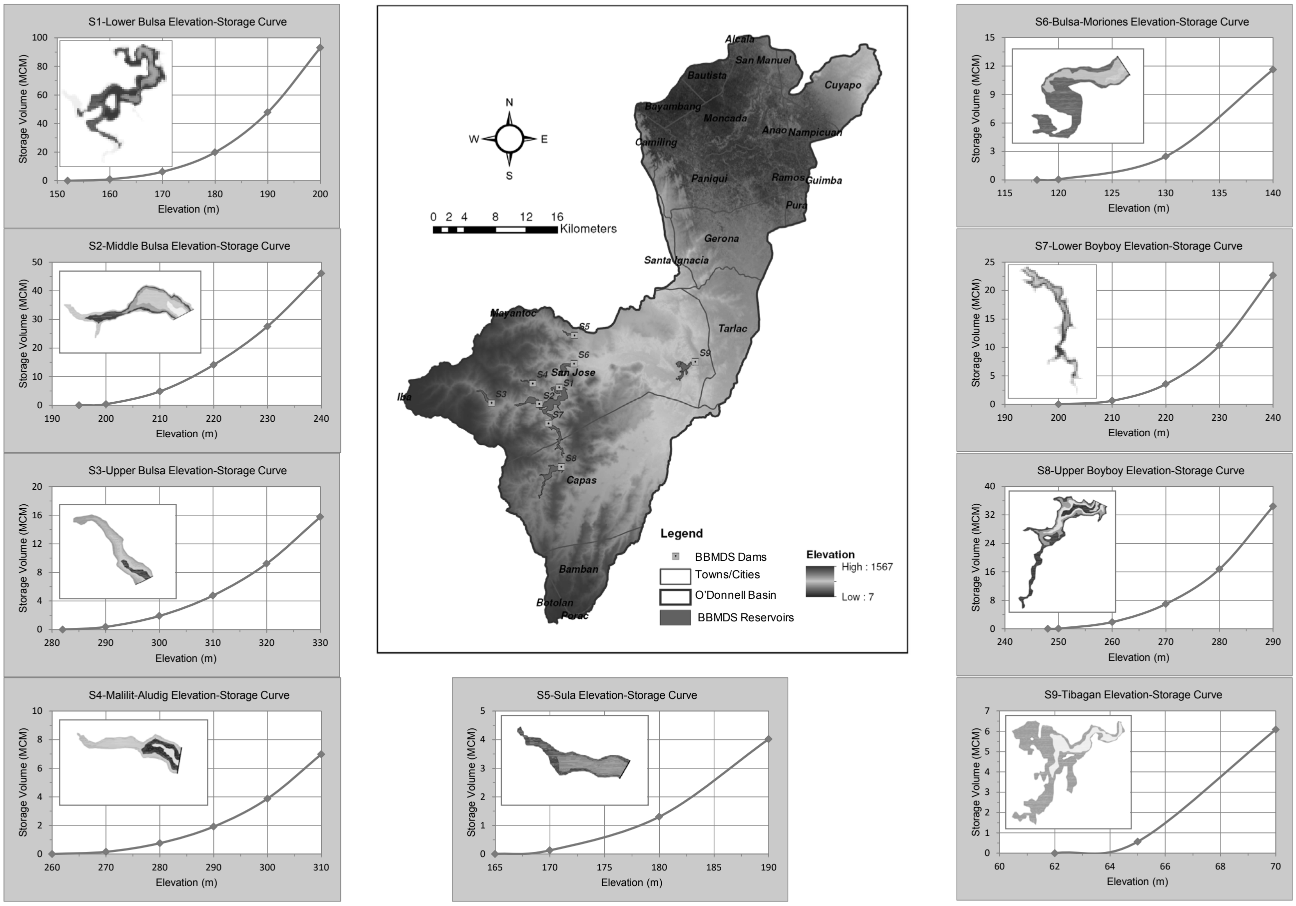


Figure 4. Location of BBMDS and reservoir elevation-area-storage curves of the nine reservoirs.

Table 1. *Specifications of the Nine BBMDS Reservoirs*

Reservoir	Dam Height (m)	Dam Elevation (m)	Dam Base Elevation (m)	Maximum Storage (MCM)
S1	48	200	152	93.09
S2	45	240	195	46.22
S3	48	330	282	15.81
S4	50	310	260	7.09
S5	25	190	165	4.02
S6	22	140	118	11.63
S7	40	240	200	22.67
S8	42	290	248	34.42
S9	8	70	62	6.08

spillway elevation is at 245 m; 3) storage capacity of 570.2 MCM at 245 m; and 4) minimum storage elevation is at 150 m. The elevation datum used here is the NAMRIA datum which is 0.0 m at mean sea level (MSL). Note that in actual dam construction, there will be a freeboard such that the dam height is higher than 95 m with the spillway crest elevation at 245 m and appropriate width to contain the design spillway flow.

Balog-Balog Multiple Dam System (BBMDS)

The Balog-Balog multiple dam systems from an unsolicited proposal (Tarlac Mini Dams Project, 2012) is to construct nine dams at the locations denoted by S1 through S9 in Figure 4. The reservoir elevation-storage curves for each reservoir are also shown in Figure 4 and pertinent reservoir specifications are given in Table 1.

Results of Optimization-Simulation Studies

The interest in reliability analysis is to evaluate the ability of the two proposed reservoir systems to provide irrigation water to Balog-Balog Irrigation system with a targeted irrigation service area of 34,000 ha. Assuming that the maximum water requirement is 1.2 m^3/s per 1,000 ha, then the total water requirement is about 40.0 m^3/s for 34,000 ha. The question here is at what level of reliability the amount of 40 m^3/s can be delivered in terms of percent-of-time per year, in the long-term. A secondary interest is the reliability of generating hydropower.

The results of the reliability analyses are shown in Tables 2 and 3 at the S1 (location of BBMP and point where 6 BBMDS reservoirs are located) and S9 (point with 9 BBMDS reservoirs), respectively. It is seen that the BBMP provides more reliable irrigation water deliveries and hydropower generation compared to BBMDS. At the S1 location, with the assumption that the water requirement is 1.2 m^3/sec per 1,000 ha, then as much as 21,027 ha can be irrigated by BBMP compared to only 17,783 ha in the BBMDS on year-round basis and both cases are higher than the case without a reservoir (natural flows), which is only 12,281 ha. During the dry season, BBMP can irrigate as much as 11,534 ha against BBMDS's 2,337 ha and without a reservoir (natural flows) only 1,679 ha. During the wet season, all three—BBMP, BBMDS, and natural flow (without a reservoir) —can irrigate as much as 26,000 ha. At location S9, the irrigation water deliveries are higher and likewise, the areas that can be irrigated are higher. In any case, at both locations (S1 and S9), the BBMP results in higher irrigation water deliveries compared to BBMDS. Definitely, the reservoirs are needed to increase the reliability of irrigation water supply upon comparing the higher reliability (percent-of-time) and corresponding larger water volumes (irrigation water deliveries) in case reservoirs in either BBMP or BBMDS schemes upon comparing the reliability (percent-of-time) associated to the case without a reservoir.

The reliability analysis of irrigation water deliveries is also performed considering reservoir sedimentation. For this purpose, the reservoir optimization-simulation study was conducted for two cases, (1) after 25 years sedimentation, and (2) after 50 years sedimentation. Based on several watersheds with reservoirs in the Philippines, the annual sediment inflow at these reservoirs is 3,500 m^3 per km^2. With this annual sediment inflow rate, Table 4 shows the number of years that BBMP and the BBMDS reservoirs will be half-filled and fully-filled. Note that four BBMDS

Table 2.
Comparison of Irrigation Water Deliveries (m^3/s) of BBMP and BBMDS (Six Reservoirs) Including Lower Bulsa River Natural Flows at S1 Location. Case with No Reservoir Sedimentation.

No Reservoir Sedimentation at S1 Location									
	All Year Round			Dry Season (Dec-Apr)			Wet Season (May-Sep)		
	Natural	BBMP	BBMDS	Natural	BBMP	BBMDS	Natural	BBMP	BBMDS
Q90 (330/140 days)*	0.96	0.96	0.55	0.77	0.77	0.14	6.86	7.51	4.60
Q80 (290/125 days)	1.35	1.93	1.18	0.96	0.96	0.52	19.08	18.02	16.95
Q60 (220/95 days)	3.76	24.00	6.48	1.25	1.64	1.08	40.00	40.00	39.71
Q40 (145/60 days)	13.40	40.00	38.80	1.73	6.26	2.21	40.00	40.00	39.99
Q20 (70/30 days)	36.53	40.00	40.00	3.86	40.00	6.82	40.00	40.00	40.00
EV(Q)**	14.74	25.23	21.32	2.01	13.84	2.80	31.89	31.83	31.17
Area Irrigated (ha)***	12,281	21,027	17,763	1,679	11,534	2,337	26,576	26,525	25,977

**Q90 (330/140 days) signifies 90% of time observed flow equal or greater than Q90 (m^3/s) 330 days over the year or 140 days over 5-month period; **EV(Q) is expected value of Q integrated over Q20 through Q90; ***Area Irrigated assuming 1.2 m^3/s per 1000 ha calculated based on EV(Q) values.*

Table 3. *Comparison of Flow Duration Curves of Daily Irrigation Water Deliveries (m^3/s) at S9 Location of BBMP System and BBMDS (Nine Reservoirs) on Year-Round, Dry Season and Wet Season Basis*

No Reservoir Sedimentation at S9 Location						
	All Year Round		Dry Season (Dec-Apr)		Wet Season (May-Sep)	
	BBMP	BBMDS	BBMP	BBMDS	BBMP	BBMDS
Q90 (330/140 days)*	1.93	0.43	1.45	0.00	14.55	29.75
Q80 (290/125 days)	3.93	3.98	1.83	0.8	33.01	37.81
Q60 (220/95 days)	34.95	26.61	3.18	3.02	40.00	39.89
Q40 (145/60 days)	40.00	39.76	13.59	8.58	40.00	39.99
Q20 (70/30 days)	40.00	39.99	40.00	23.54	40.00	40.00
EV(Q)**	27.87	25.94	15.85	9.39	35.13	38.11
Area Irrigated (ha)***	23,223	21,614	13,205	7,828	29,279	31,758

**Q90 (330/140 days) signifies that the observed flow ≥ Q90 (m^3/s), 90% of the time or 330 days a year or 140 days over the 5-month period; **EV(Q) is expected value of Q integrated over Q20 through Q90; ***Area Irrigated assuming 1.2 m^3/s per 1000 ha calculated based on EV(Q) values.*

Table 4. *Reservoir Life Computations Due to Sedimentation with a Sediment Inflow of 3500 m^3/year/km^2 for BBMP and BBMDS Reservoirs (MCM is million m^3)*

		Drainage Area (km^2)	Annual Sediment Inflows (MCM)	Starting Storage (MCM)	Half-Filled Storage (MCM)	Year to Half-Filled Reservoir	Years to Fully-Filled Reservoir
BBMP Single, High Dam		289.31	1.013	648.97	324.49	321	641
BBMDS Dams	S1	36.43	0.128	93.09	46.54	366	731
	S2	48.74	0.171	46.10	23.05	136	271
	S3	67.34	0.236	15.77	7.89	34	67
	S4	24.65	0.086	6.98	3.49	41	81
	S5	41.62	0.146	4.02	2.01	14	28
	S6	10.36	0.036	11.63	5.81	161	321
	S7	42.91	0.150	22.67	11.33	76	151
	S8	69.23	0.242	34.42	17.21	72	143
	S9	182.27	0.638	6.08	3.04	5	10

reservoirs namely, S3, S4, S5, and S9, can be half-filled in less than 40 years while BBMP takes 321 years to be half-filled. In the reservoir optimization-simulation model, the reservoir sedimentation is accounted for by modifying the reservoir elevation-storage curves for the two cases, that is, after 25 years sedimentation and 50 years sedimentation.

As shown in Table 5, based on 50 years reservoir sedimentation, BBMP still results in higher irrigation water deliveries and thus, higher irrigated areas compared to BBMDS at both locations S1.

With regard to potential hydropower generation as shown in Table 6, generally BBMP (with one hydropower plant) versus BBMDS multiple reservoir system (with five hydropower plants located at S1, S2, S3, S4, and S5) result in higher hydropower generation and subsequently higher annual revenue, assuming the selling price of electricity is PhP3 per kW-hour, with no sedimentation (base year condition), after 25 years sedimentation and after 50 years sedimentation. Note that the hydropower generation gets higher as sediment accumulate since reservoirs during those periods will

Table 5. *Comparison of Flow Duration Curves of Daily Irrigation Water Deliveries (m^3/s) at S1 Location of BBMP System and BBMDS (Six reservoirs) on Year-Round, Dry Season and Wet Season Basis with 50 Years Sedimentation*

	After 50 years with Reservoir Sedimentation					
	All Year Round		**Dry Season (Dec-Apr)**		**Wet Season (May-Sep)**	
	BBMP	**BBMDS**	**BBMP**	**BBMDS**	**BBMP**	**BBMDS**
Q90 (330/140 days)*	1.06	1.06	0.77	0.00	7.511	5.737
Q80 (290/125 days)	1.93	1.93	0.96	0.08	18.02	18.14
Q60 (220/95 days)	21.03	20.24	1.64	0.83	40.00	39.78
Q40 (145/60 days)	40.00	40.00	6.27	1.98	40.00	40.00
Q20 (70/30 days)	40.00	40.00	40.00	5.52	40.00	40.00
EV(Q)**	24.65	20.42	13.84	2.23	31.83	31.54
Area Irrigated (ha)***	20,545	20.414	11,534	1,858	26,525	26,280

**Q90 (330/140 days) signifies that the observed flow ≥ Q90 (m^3/s), 90% of the time or 330 days a year or 140 days over the 5-month period; **EV(Q) is expected value of Q integrated over Q20 through Q90; ***Area Irrigated assuming 1.2 m^3/s per 1000 ha calculated based on EV(Q) values.*

Table 6. *Hydropower Generation (in MW) at BBMP (One Hydropower Plant) Versus BBMDS Project (Five Hydropower Plants Located at S1, S2, S3, S4, and S5)*

	Hydropower Generation in MW for 10 hours Daily Operations					
	No Sedimentation		**After 25 Years Sedimentation**		**After 50 Years Sedimentation**	
	BBMP	**BBMDS**	**BBMP**	**BBMDS**	**BBMP**	**BBMDS**
Q90 (330 days)*	0.00	1.24	0.78	1.79	0.99	1.91
Q80 (290 days)	0.00	3.65	1.42	4.77	1.81	5.09
Q60 (220 days)	1.59	7.01	16.94	9.98	20.19	10.53
Q40 (145 days)	38.46	22.99	43.28	32.85	47.64	34.25
Q20 (70 days)	60.38	60.32	62.65	64.37	64.75	65.09
EV(Q)**	26.13	24.83	31.17	28.86	33.41	29.53
GW-hours/year	95.36	90.63	113.76	105.35	121.94	107.79
Annual Revenue in million pesos at 3 pesos per KW-hour	286	272	341	316	366	323

**Q90 (330 days) signifies that the observed flow ≥ Q90 (m^3/s), 90% of the time or 330 days a year; **EV(Q) is expected value of Q integrated over Q20 through Q90. Also KW, MW and GW for kilo, mega and giga watts.*

be operating at higher reservoir elevations but the tailhead elevations of hydropower plants are assumed to be the same when it was constructed.

As far as the cost of dams is concerned, BBMP dam costs PhP3.99 billion compared to BBMDS's nine small dams total cost of PhP5.08 billion. BBMDS scheme results in higher costs because there are more clay core and rockfill materials needed to build the nine dams compared to BBMP single dam and noting that the clay core is more expensive than the rockfill materials.

From results of economic analysis given in Table 7, assuming benefits from growing 13 crops, the B/C ratios, NPVs, and EIRRs for all BBMP are all higher compared to those for BBMDS. The EIRRs while all above 15%, the estimates for BBMDS are nearer the

Table 7. *Estimates of B/C Ratio, Net Present Values and IRR for BBMP and Multiple Dam Project for Base Case, After 25 Years, and After 50 Years with Sedimentation (Irrigation Benefits for Rice, Sugarcane, Corn, Potato, Eggplant, Tomato, String Beans, Ampalaya, etc. but Excludes Hydropower)*

Indicator	Base Case		Base Case plus higher investment & 20% less irrigation benefits		Case with 25 years reservoir sedimentation		Case with 50 years reservoir sedimentation	
	BBMP	BBMDS	BBMP	BBMDS	BBMP	BBMDS	BBMP	BBMDS
B/C Ratio	2.77	1.67	1.84	1.12	2.73	1.19	2.71	1.16
NPV @ 15% (million pesos)	6,128	2,972	3,514	612	5,991	819	5,921	703
EIRR	27	20	21	16	27	17	27	16

Table 8. *Flood inundated areas such as towns of Santa Maria, Santo Nino, Mapalad, and Santa Cruz located downstream of BBMP and BBMDS.*

Scenario	Discharge (m^3/s)	Time Sustained (hr)	Total Flood Volume (MCM)	Total Flooded Area (ha)	Average Flood Depth (m)
Natural	3650	3	3.942	120.26	3.28
BBMP	1980	3	2.138	96.07	2.23
BBMDS	3200	3	3.456	120.26	2.87
Natural	3650	5	6.570	157.93	4.16
BBMP	1980	5	3.564	120.26	2.96
BBMDS	3200	5	5.760	157.93	3.65

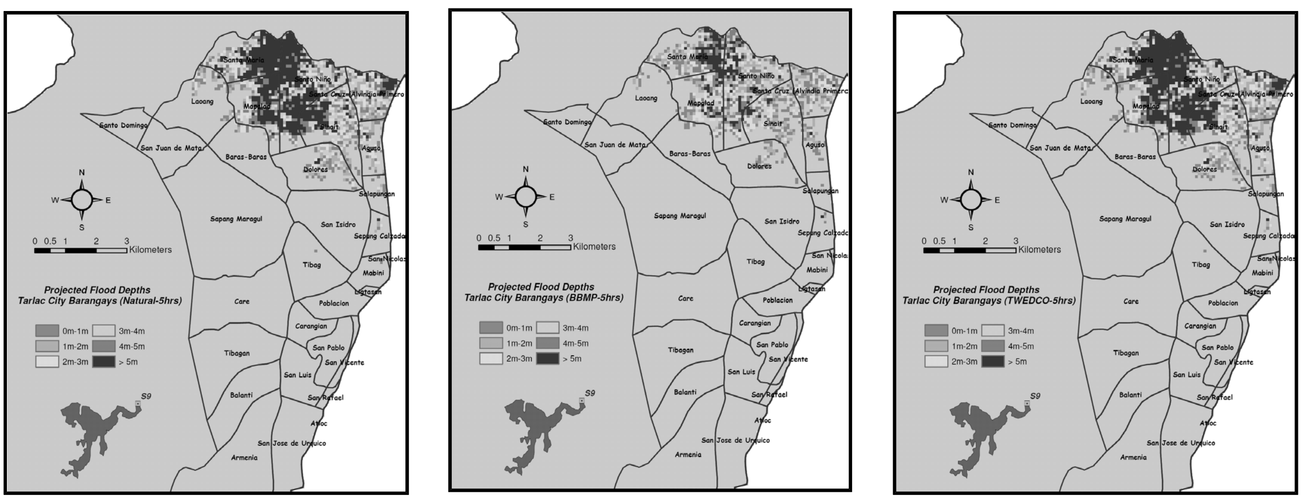
cut-off at 16-17%, even for the worst scenario (with reservoir sedimentation). Similarly, the NPVs while all positive, those for BBMDS are a small fraction of those for BBMP. The same is true for B/C ratios which are all above 1.0 with those for BBMP much higher. The above analysis reveals that while both projects appear to be economically viable based on the three economic indicators, the BBMP seems better. Going for more conservative estimates of benefits, with only two crops assumed to benefit from the project, the results obtained show a dismal picture for BBMDS. BBMP remains a better choice but this time, BBMDS's proposal becomes unviable based on all three measures—benefit-cost (B/C) ratio, net present value (NPV), and economic internal rate of return (EIRR).

With regard to the reservoir backwater inundated areas, number of households that can be inundated at full reservoir capacity is 330 households for BBMP dam against 448 households for the nine BBMDS dams, respectively. With these estimates of the number of households affected, corresponding resettlement costs can be calculated.

Finally, with regard to flood benefits, Table 8 shows flood statistics with accompanying Figures 5 and 6. It is seen here that BBMP has reduced the natural annual maxima daily flow (equivalent to 50-yr return period flow) from about 3,600 m^3/sec to about 1,980 m^3/sec (a difference of 1,670 m^3/sec) while BBMDS scheme only reduced this natural 50-yr return-period daily flow to 3,200 m^3/sec (or a difference of 400 m^3/sec). The flood inundated areas and corresponding average flood depth are lowest with BBMP compared to the case with BBMDS and natural river condition (without the reservoir). The BBMDS scheme and natural river flows (without a reservoir) result in the same flood inundated areas but the flood inundated depths are lower for BBMDS.

(a) without a reservoir (b) with BBMP (c) with BBMDS

Figure 5. Flood inundated areas with sustained flows of 3 hours.



(a) without a reservoir (b) with BBMP (c) with BBMDS

Figure 6. Flood inundated areas with sustained flows of 5 hours.

Alternative Water Source to Balog-Balog Irrigation System

As seen in the results of reliability analysis earlier, the BBMP single reservoir scheme (even lesser with BBMDS) can only irrigate an average of 23,000 ha for two cropping seasons (13,000 ha for dry season and 29,000 ha for wet). However, since the target service area of the Balog-Balog Irrigation System is 34,000 ha, then an alternative irrigation water source is needed. For this matter, Figure 7 shows that since the Balog-Balog irrigation system service area extends to the Rio Chico River and Talavera River systems, then this should be explored and examined in more detail on how these river systems can be used to augment the water for the Balog-Balog irrigation system. Note that Rio Chico River and Talavera River basins drain into the Pampanga River basin while the Tarlac-O'Donnell River basin drains into the Agno River basin.

Conclusions

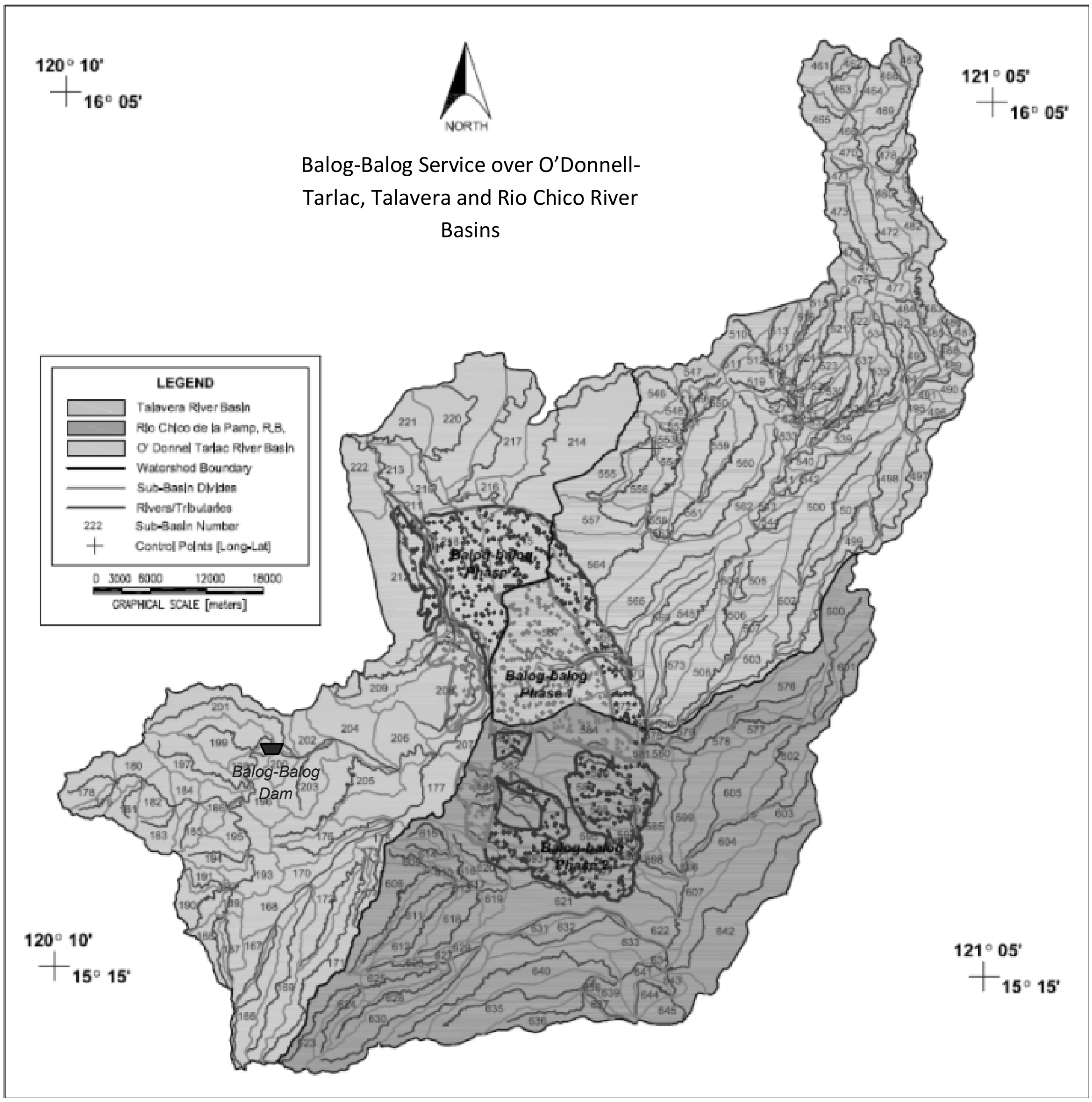


Figure 7. Map showing the Balog-Balog Irrigation System service area traversing three major watersheds, namely: O'Donnell, Rio Chico, and Talavera river basins.

The BBMP with a single, high dam provides more reliable irrigation water deliveries and hydropower generation compared to BBMDS with nine low dams. In terms of dam cost, BBMP has a lower cost of PhP3.99 billion compared to BBMDS's nine low dams totaling PhP5.08 billion. Likewise, the economic analysis results indicate higher B/C ratios, NPV, and IRR for BBMP compared to BBMDS scheme. With reservoir sedimentation, BBMDS with relatively small storage-size dams have shorter lives where 4 out of 9 will be half-filled in less than 40 years compared to BBMP's single dam to be half-filled in 320 years. Also, BBMP has better flood control function compared to BBMDS. As a final comment, since the BBMP and BBMDS (even lesser) can only irrigate an average of 23,000 ha, the Talavera and Rio Chico Rivers should be explored as alternative water source for Balog-Balog Irrigation System since its target service area is 34,000 ha.

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