Reservoir Operation for Recession Agriculture in Mekong Basin, Laos

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Abstract: As hydropower dam construction in rapidly growing economies dislodges communities, rural development experts must help the displaced make their livelihoods in new lacustrine environments. One question is whether the dam infrastructure can directly benefit those who remain within the vicinity of the reservoir. Integrated water resource management seeks to concurrently consider hydrological, socioeconomic, and ecological factors, yet water managers lack the information needed to include livelihoods in their analyses. The objective of this paper is to develop tools and plans for coordinating hydropower reservoir operation and management for rural livelihoods. Specifically, this study investigates how dam management may accommodate vegetable farming on the banks of a reservoir. The intervention investigated is to lower water levels during the cultivation period in order to expose shoreline gardens. Based on the recession agriculture rule, evaluated through simulation of a dam in Lao People's Democratic Republic, the average annual hydropower production was reduced by between 0.4 and 8.1%, depending on the agricultural goal, with the loss to power occurring mainly in the months April to June. By focusing on hydropower reservoir systems, the techniques developed in this study have the potential to be applied to support communities throughout the world that farm on the shorelines of water reservoirs. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000485. *© 2014 American Society of Civil Engineers.*

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Introduction

As of 2010, the World Bank had reserved over $2 billion for dam construction (Foster and Briceño-Garmendia 2010), having approved 67 hydropower projects since 2003 (Goodland 2010). Dams, financed by many private, multilateral, and governmental organizations, have displaced between 40 and 80 million people, many of whom lost their livelihoods (Goodland 2010). As hydropower and storage reservoirs are constructed in Africa and Asia, strategies need to be developed that mitigate losses to local economies without conceding regional or national benefits.

Integrated water resource management (IWRM) gained prominence in the 1990s following the recognition that water resources had been developed for national and international benefit, but on the local level only the costs of these developments are experienced, not the rewards (Molle 2009). Some have argued that livelihood management is the next factor to be integrated into an IWRM perspective (Merrey et al. 2005). To achieve integration, researchers have called for hydrological models of shared benefits to provide evidence of the potential gains and losses (Lautze and Kirshen 2007; McCartney 2007). One study from Senegal simulated increased dam releases for farmers downstream and argued that the resulting cost of reduced hydropower needs to be considered in the context of potential displacement of farmers if their livelihood needs cannot be met (Fraval et al. 2002). Another study considered livelihoods in reservoir operation using dynamic programming to optimize the ideal water level for fish catch and irrigation storage in a reservoir in Vietnam, but it did not develop dam operational rules or consider the impact of livelihoods on hydropower production (Tran et al. 2011). Dam systems in Brazil were simulated to include water uses for livelihoods that are typically neglected, including agriculture and aquaculture (Pulido-Velazquez et al. 2013; Hurford et al. 2014).

Multiple factors complicate reservoir simulation. For ungauged basins, reservoir inflow must be estimated. Evaporation, leakage, and seepage within a reservoir system are rarely understood well and are difficult to measure (Kay and Davies 2008). Even when historical data have been collected, future hydrological parameters are subject to climate change (Intergovernmental Panel on Climate Change 2007; Karl and Trenberth 2003; Keskinen et al. 2010). With so much uncertainty, even carefully assembled data sets and patched time series may suffer large errors. Typically, a model can be considered valid when there is reasonable agreement between the historical data and simulation results. In the case of a newly constructed dam, however, the operation of these new facilities is based on estimates of future conditions, without historical water level data to calibrate a baseline model. As with all other new dams, the assumed baseline can be compared to alternative operation models developed to investigate the goals of water resource management.

Water Resources Case Study in the Lower Mekong Basin

The Mekong River, the longest river in Southeast Asia, and its tributaries support the agriculture, fishing, and forestry livelihoods of the 60 million people who live in the Mekong River Basin.

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Eighty-five percent of the basin residents live at a subsistence level (Bruhl and Waters 2009). According to the Mekong River Commission (MRC), overall, it is estimated that approximately 29.6 million people live within 15 km of the main channel, and within this corridor there are high levels of dependence on water resources for food and income (Hall and Bouapao 2010). The Mekong Basin development is in a period of rapid growth. The current active storage capacity in reservoirs along the Mekong River is 9.35 km^3. The planned storage is over 107 km^3 (MRC 2011) to capitalize on 30,000 MW of potential in the Lower Mekong Basin (LMB) (Bird and Phonekeo 2010; Hall and Bouapao 2010; MRC 2010). While water storage infrastructure can supply irrigation projects, in hilly or mountainous regions, the newly submerged terrain may have been the most productive agricultural land. Consequently, the national economic benefit of dam development is seen as existing in conflict with the negative impact on farming in the Mekong Basin. Yet, the MRC estimated that altered flow regime in the Mekong River could be worth US$17 million from vegetable revenue (MRC 2005).

The case study of this paper is the Nam Gnouang (NG) dam on the Gnouang River, located in the Bolikhamxay Province of eastern central Lao People's Democratic Republic (Lao PDR) (Fig. 1). Water resource infrastructure development for hydropower is central to the Lao PDR national strategy for development. This area, like most of Lao PDR, has a wet–dry tropical climate, as defined in the Köppen classification (Peel et al. 2007). The peaked seasonal hydrograph makes water storage more important for hydropower generation after the monsoon season, which falls between June and November.

Fig. 1 shows the NG and Theun-Hinboun Expansion Project (THXP) dams, the latter located along the Theun River, and all of the gauging stations and other features described in this paper. The characteristics of the NG and THXP dams are shown in Table 1. The NG reservoir was constructed in 2011 in part to supply flows lost due to another diversion project, the Nam Theun 2 (NT2) dam, whose spillway discharges into the Theun River. The NG reservoir doubles the capacity of the downstream THXP dam reservoir and tunnel system diverting water from the Theun to the Hinboun River. Residents displaced by the NG dam, previously residing in four former villagers (Phonkeo, Saensi, Sopchat, and Thambing), were resettled in Keosenkham (Fig. 1). These villagers benefited by receiving community water taps, household electricity, and cash as compensation from the Theun Hinboun Power Company (THPC), among other benefits, but lost all their rice paddies, which were along the banks of the now-flooded Gnouang River (Katus 2012). Vegetable cultivation in gardens along the shorelines of the reservoir could help offset the losses from rice farming. The modest contribution to income and subsistence from vegetable gardens should be considered in the context of the poverty known to the resettlement community. However, under current operations, many shoreline gardens are also submerged for part of the growing season.

Methods

This work develops a simulation model, given upstream flows, average releases from NT2, rainfall, and evapotranspiration, to predict the water levels and releases from the NG reservoir and the power production at THXP for the period from 1986 to 2011. A baseline model and results are developed based on reservoir operation goals of the THPC. Alternative operating rules are also developed to support the livelihoods of shoreline gardening. The results are then compared with the alternative rules for livelihood support to the baseline results.

Baseline Simulation

A reservoir simulation model of the THXP reservoir system was developed using *ResSim* (Klipsche and Hurst 2007). Table 2 shows

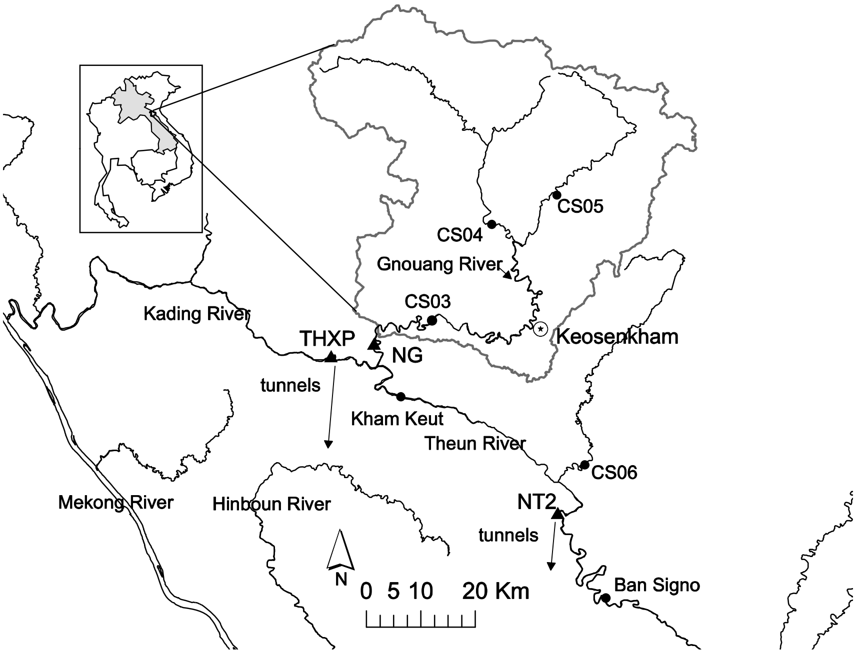

Fig. 1. Nam Gnouang catchment in Lao PDR (thick gray line), with river gauging stations (circles), hydropower dams (triangles), tunnel diversions (arrows), and other relevant features. Surrounding Lower Mekong Basin countries shown in insert (clockwise from upper left: Thailand, Laos, Vietnam, and Cambodia); the flow is modeled in the reaches between the NG and THXP dams and Kham Keut station; shoreline gardens occur from Keosenkham to the confluence of streams leading to the Gnouang River

Table 1. Physical Characteristics of Nam Gnouang and THXP Dams

Dam trait	Nam Gnouang	THXP
Crest	473 masl	402 masl
Average tailwater	400 masl	175 masl
Maximum storage	3,000 Mm^3	58 Mm^3
Capacity	134 MW	220 MW

Note: THXP = Theun-Hinboun Expansion Project.

Table 2. Catchment Area of Gauging Stations (CS03-06, Kham Keut, and Ban Signo) and Dams (NG, THXP, and NT2), Shown from North to South

Name	Area (km^2)
CS05	486
CS04	1,300
CS03	2,595
NG	2,830
THXP	8,937
Kham Keut	5,820
CS06	1,190
NT2	4,013
Ban Signo	3,370

Note: NG = Nam Gnouang; NT2 = Nam Theun 2; THXP = Theun-Hinboun Expansion Project.

the catchment areas of the gauging stations and dams along the Theun and Gnouang Rivers. Gauging stations along the Gnouang River were installed within the last decade, while the gauging station Kham Keut, along the Theun River, was active for just 5 nonconsecutive years. The NG dam construction was only completed in 2011, and the historical flow record was not available to calibrate the simulation results and demonstrate the hydrologic impact of the NG dam.

Given the limitations of existing data, several methods of calculating inflows to the NG and THXP dams were considered. Using a flow duration curve (FDC) method (Hughes and Smakhtin 1996), the stream flow gauged at the station Ban Signo, which has the longest duration of recorded flows in the region, was used to calculate the inflows to gauging station CS03 prior to 2001 when the NG catchment was not gauged. The magnitude of flow at CS03 (2001–2010) corresponding to the percentile (per month) of the flow at Ban Signo was assigned for each day missing gauged flow. For example, on February 1, 1986, the Ban Signo flow of 43 m^3/s corresponds to the 90.7% flow in all Februaries, which represents a 38.0 m^3/s flow at CS03 from all Februaries.

The FDC-calculated (1986–2000) and gauged (2001–2011) time series of flows at CS03 (1986–2000 and 2001–2011, respectively) were multiplied by the ratio of area of the catchments to approximate the inflows to the NG reservoir (Fig. 2). The FDC method was also performed to estimate the flows for the ungauged years at Kham Keut using the gauged streamflow at Ban Signo. Then the calculated and observed time series at Kham Keut were scaled to the area of the catchment of the Theun River at the confluence with the Gnouang River, with the NT2 catchment area subtracted to account for the NT2 tunnel diversion (Fig. 1). This composite time series was added to the average spillway releases from the NT2 dam (Norplan 2008) to simulate the inflow from the Theun River into the THXP dam.

Operational rules to determine release rates from the NG reservoir (Q_{NG} in m^3/s), composed of several logical statements, were developed in *ResSim*'s Jython interface. The baseline rule, which simulates a typical operation scheme for hydropower management at the NG reservoir, is defined as follows:

$$Q_{\mathrm{NG1}} = 205\ \mathrm{m}^3/\mathrm{s} - Q_{\mathrm{NT}} \tag{1}$$

$$Q_{\mathrm{NG2}} = \frac{S_{\max} - S_{\min}}{4\ \mathrm{month} \times 30.4\ \mathrm{d} \times 24\ \mathrm{h} \times 3600\ \mathrm{s}} \tag{2}$$

$$\text{Wet season: } Q_{\mathrm{NG}} = Q_{\mathrm{NG1}} \tag{3a}$$

$$\text{Dry season: } Q_{\mathrm{NG}} = \min(Q_{\mathrm{NG1}}, Q_{\mathrm{NG2}}) \tag{3b}$$

Statement 1 requires the confluence of the flows in the Theun (Q_{NT}) and Gnouang Rivers to be 205 m^3/s, which is the sum of the THPC demand for hydropower generation in the THXP tunnels (the optimal capacity of 200 m^3/s) and a small requisite environmental flow into the Kading River (5 m^3/s). Statement 2 is used to simulate the release of a constant volume over the dry season (December–June), where $S_{\max}$ is the NG reservoir storage on October 31 and $S_{\min}$ is the minimum storage of 420 m. Statement 2 approximates the release profile that the THPC leaders described

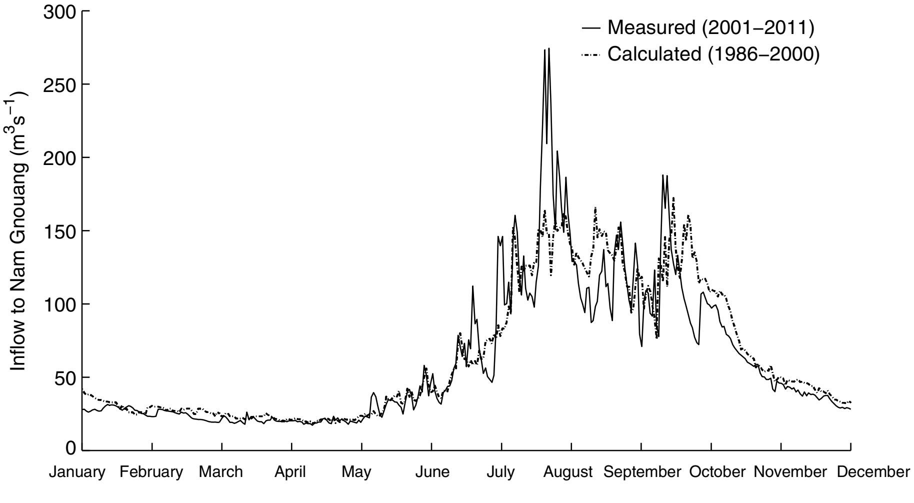

Fig. 2. Median time series of daily flow to NG Dam gauged (2001–2011) and calculated (1986–2000) using flow duration curve method

in meetings (R. Allen, personal communication, 2012). During the wet season, the release is determined by Statement 3a, while during the dry season Statement 3b is used.

A further restriction is that the water level in the NG reservoir must be above levels set by the Thai power purchaser. The company has stated that the main criterion for dam operation is the hydropower production at the downstream tunnels of the THXP reservoir because flooding downstream of the NG Dam is not a concern. Power is simulated by *ResSim* using the following statement:

$$P = eQ_T\gamma H \tag{4}$$

where P = power generated in watts (W); e = efficiency of hydroelectric system, assumed to be 95%; Q_T = flow through turbines (m^3/s); γ = specific weight of water ($9.81\ \mathrm{KN/m}^3$); and H = effective head (m).

A series of figures characterizes the baseline operation of the NG Dam. These figures help to highlight both hydrologically key areas for interventions and potential vulnerabilities of changing the reservoir operation to support livelihoods. Fig. 3 shows the intra- and interannual baseline water level variations (m) in the NG reservoir. The water level typically reaches the minimum of 420 m in virtually all years but reaches the full supply level of 455 m in just 6 out of 25 years. Fig. 4 shows the daily median total flow out from the dam (m^3/s) and water level (m) in the baseline NG simulation. Note that the median outflows are less than the target release of 205 m^3/s. As shown, there is a steep drop in the outflow toward the end of April when the elevation in the NG reservoir approaches 420 m, at which point outflows simply match inflows. During the wet season, there are often no releases from the NG dam (Fig. 4) because the flows from the Theun River are sufficient to meet the downstream power demand and the environmental flow release requirement. During the dry season, the interquartile range of releases is approximately 50 m^3/s, while the variation during the wet season is much greater. Since the dam only came online in 2012, as noted earlier, these baseline simulations cannot be calibrated to historical operation data; nevertheless, the water level and release profiles qualitatively match those described by the dam company (R. Allen, personal communication, 2012). When the inflow to the THXP dam is insufficient and cannot be compensated by THXP storage releases, the baseline power production at THXP declines. In the baseline simulations, the optimal capacity of 400 MW is met more than half of all days, and 18 MW is exceeded on 99% of the days.

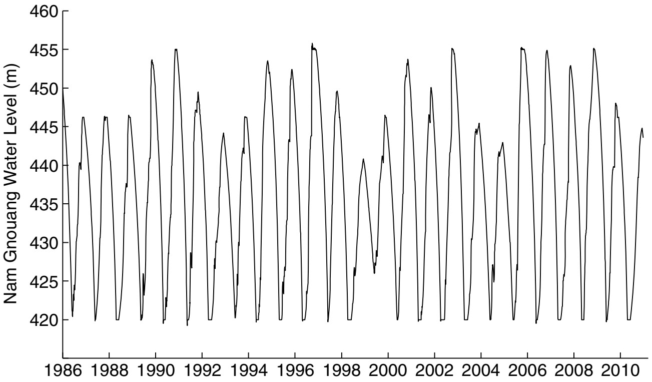

Fig. 3. Baseline water level (m) of NG reservoir

Integrating Recession Agriculture Goals into Reservoir Operations

The reservoir operation and recession agriculture interact such that the land and water resources may be managed together. Prolonging specific low water levels may allow cultivation of profitable vegetables on exposed shorelines. In the recession agriculture alternative model, the reservoir water level will be drawn down to expose the shoreline gardens during the growing season. The gardens at the preresettlement villages were selected because some farmers prefer to return there rather than farm in new locations due to concerns about garden fertility (Reis et al., unpublished data, 2012). Not all farmers will be able to return to old gardens due to fuel costs for the boat journey and labor costs. New sites to cultivate closer to Keosenkham are also considered.

In addition to geographical considerations, the timing and duration of the crop seasons must be considered. Shoreline gardens can be cultivated in the dry season (December–May); some crops (e.g., chili and long bean) can be harvested during the wet season. The second gardening season begins in April and can last through August (Douangsavanh 2011; Reis et al., unpublished data, 2012). The crop calendars of the vegetables traditionally grown in the area were compared to the typical exposure of shoreline gardens to find the arability of gardens during the crop cycles (shown with results in Fig. 5). Farmers can plant vegetables, such as greens, that have a shorter growing season in lower-elevation gardens. Shoreline gardens further upstream (in Thambing and Sopchat) will have a longer exposure period, enabling crops such as eggplant to be

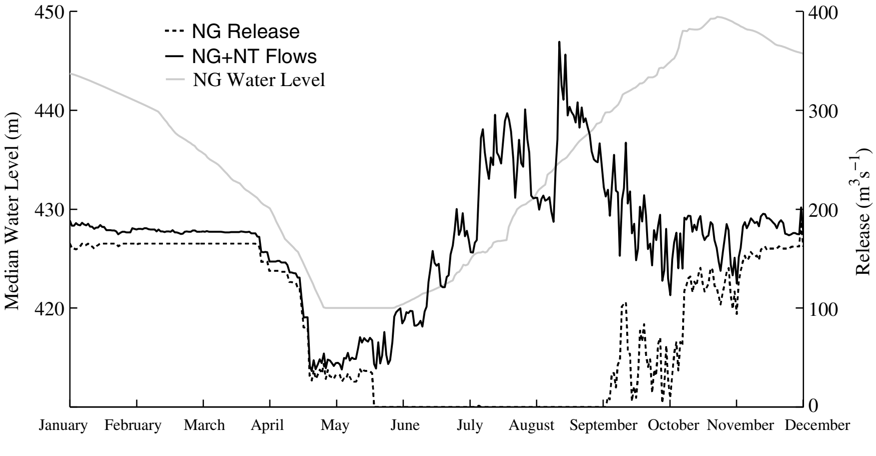

Fig. 4. Median releases from NG Dam, inflows to THXP Dam (combined flow from NT and NG), and water level in NG Dam for baseline model

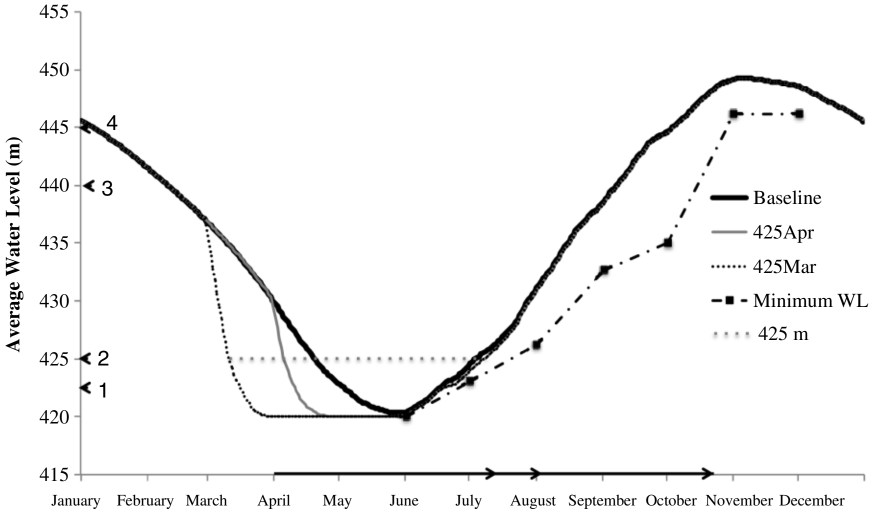

Fig. 5. Average elevation of water level of NG reservoir in baseline and recession agriculture models 425Apr and 425Mar; the minimum water level (WL) displays the restrictions on reservoir operation that reduce season for shoreline gardening; numbers along y-axis represent lowest elevation of gardens at each of four former villages (1 = Phonkeo, 2 = Saensi, 3 = Thambing, 4 = Sopchat); arrows along *x*-axis represent season of sample crops that could be grown on shores of reservoir (respectively green vegetables, eggplant, and chili)

harvested later in the year. Some vegetables, such as chili, can be harvested for several months, and to maximize the harvest these crops could be grown in upland gardens. Upstream gardens have a lower risk of late-season flooding but may require irrigation. The water volume needed, however, would be trivial compared to the storage in the NG reservoir, even at the minimum operating capacity (at 420 m, when the storage is 189 Mm^3).

To integrate recession agriculture into the reservoir operations, several rules were developed and tested. The recession agriculture rule 425Apr keeps the water level at or below 425 m during the growing season of April–August. Rule 425Mar draws down the water levels to 425 m from March to August to create a longer growing season. The rules are overridden during the monsoon season when the water level is required by the Thai power purchaser to be higher than 425 m (shown with results in Fig. 5). For example, at the end of August the legal minimum reservoir elevation is 433 m, so even with the recession agriculture rule the lower elevation gardens in the old villages of Phonkeo and Saensi will be flooded.

To estimate the exposure period for gardening resulting from the altered reservoir operation, geospatial analysis (Kam 2013) that classified the shoreline area of the reservoir was leveraged. For the analysis in this paper, land is considered suitable when it is within 2 h and 10 min (traveling by boat) of the landing dock by Keosenkham, has a slope of 12.5% or less, and is adjacent to the NG reservoir (areas are listed in Table 3). The maximum travel time from Keosenkham to the farthest village, Saensi, was selected as a benchmark for this study.

The exposure (E) is used as a metric to estimate the total growing area above the water level and is used to compare alternatives. E is defined by the following equation:

$$E = \sum_{n=1}^{7} p_n a_n \tag{5}$$

where a_n = potential gardening area above the elevation, as shown in Table 3; and p_n = probability that the water level ranks at elevation n. For example, for number 6, the baseline water level is between 440 m and 445 m for 4.0% of days in the March–August period (longest growing season, as specified for 425Mar), so the exposure for the interval is the weighted area above this interval, or $0.040 \times 13.5\ \mathrm{ha} = 0.54\ \mathrm{ha}$. E, then, is the total of exposure of all elevation intervals where riverbank gardens are feasible.

Table 3. Number Corresponding to Maximum Water Level (m) and Exposed Area (ha) of Land Considered Suitable for Shoreline Gardening

Number	Water level (m)	Exposed area (ha)
1	420	53.3
2	425	48.6
3	430	42.7
4	435	33.2
5	440	23.7
6	445	13.5
7	450	4.0

Numerical Experiments

Several numerical experiments were performed by simulating the following models: hourly, constant demand, maximum flow, and agricultural targets. As is typical of hydropower plants, the THXP reservoir will be operated on a peaking schedule (R. Allen, personal communication, 2012). The hourly model accounts for a peaking schedule that would release hydropower during peak electrical use and conserve storage during nights and weekends, the hours of lowest electrical usage. The release rule script for the NG dam was modified to accommodate an hourly model. The THXP baseline demand of 200 m^3/s for optimal power demand was multiplied by an assumed fraction for each hour and day of the week, as shown in Table 4; the average demand simulated for the hourly model is thus 86 m^3/s. Accordingly, the results of the hourly baseline and hourly 425Mar power generation are compared, as opposed to the results of the daily and hourly models. The lower releases during nights and weekends allow the water level of the THXP reservoir, which has very little storage (41.8 Mm^3 at the normal operating level of 400 m, representing just 1.4% of the total storage of the NG reservoir), to refill after the high releases during the day, a volume equivalent to 2.4 days of continuous target releases (200 m^3/s). To limit computational time, only one gardening rule

Table 4. Fraction of Optimal Release for Hydropower Used in Hourly Model

Hour	Demand fraction	Day	Demand fraction
1–6	0.1	Sunday	0.3
7	0.4	Monday	1
8	0.5	Tuesday	1
9–19	1	Wednesday	1
20	0.4	Thursday	1
21	0.2	Frdiay	1
22–24	0.1	Saturday	0.3

was modeled. The 425Mar garden rule was used for the hourly model to find the largest possible impact on the hydropower of the operational rule for agriculture.

To test whether a computationally simplified model with a constant demand could approximate the hourly operation, a daily model with a constant power demand corresponding to the optimal tunnel capacity and an hourly model with average peaking hydropower schedule, 86 m^3/s, was simulated. The 425Apr and 425Mar gardening rules were examined with respect to the effects on water level in the NG reservoir and hydropower at the downstream THXP dam and on the risk of flooding the gardens.

Although the THPC does not consider flood control to be a goal of dam operation (R. Allen, personal communication, 2012), this work developed a maximum flow rule (MaxQ) to limit outflows. Use of MaxQ allows determination of the impact of flood control on agricultural goals. With no knowledge of the channel capacity below the NG dam, a maximum release of 500 m^3/s, which is over twice the target release through the THXP tunnels, was chosen. For the baseline, which does not have a maximum flow rule, a flow of at least 500 m^3/s was only released from NG outlets 0.3% of the days simulated.

To evaluate whether the gardening benefits of altered dam operation are concentrated at certain elevations, the agricultural targets model modifies the rules 425Apr and 425Mar, which lower the water level to 425 m by April and March, respectively. Agricultural targets draws the water level to 430 m and 435 m in April and March each, thereby creating four new alternatives—430Apr, 430Mar, 435Apr, and 435Mar.

Results

The recession agriculture rules drew down the water level in the NG reservoir starting in April (425Apr) or March (425Mar). The average water levels are shown in Fig. 5. In the daily model with a constant demand of 205 m^3/s, the garden rules and 425Mar reduced the water level in the NG reservoir by an average of 0.6 and 1.6 m and lowered overall hydropower generation by 3 and 8%, respectively. Garden exposure E, as defined by Eq. (5), increased by 2.9 and 3.9%, respectively, for 425Apr and 425Mar. In all four of the preresettlement villages, some of the gardens along the reservoir shoreline will be submerged in the baseline average (Fig. 5). No tradeoff between exposure length and risk of submersion of shoreline gardens, measured by the number of times that the lowest gardens are submerged, was found. Very little or no water is released from the NG dam during the wet season because of the high flows at Kham Keut.

When the water level drops below the minimum legal elevation due to releases made in a single day, no more releases are made until the level rises above the minimum. Fig. 6 shows the daily percent exceedance for the water level in the NG reservoir for the months during the gardening season (April–July). As shown, the agricultural measures reliably draw the water level to the elevations prescribed at the start of the growing period. They are not effective for July and August because of the minimum water elevation (Fig. 5). The only reduction in water level occurs over March–June, the period when the drawdown rules for 425Apr and 425Mar are active (Fig. 6).

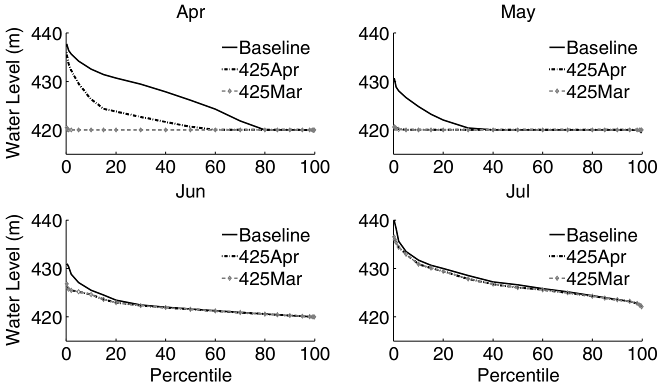

Fig. 6. Percent exceedence curves for daily water level in NG reservoir for baseline, 425Apr, and 425Mar models for months April–July

Even in a dry year, the NG reservoir has ample water to meet the needs of small shoreline farmers (Table 1). During the wettest year in the simulation study, 1996, the exposure of land available for shoreline farming was slightly lower than the average exposure (Table 5). During the following year, 1997, the loss of exposure was greater than during the 1996 flood. The land exposure was most reduced below 430 m and during the start of the growing season, so the lower elevation gardens (e.g., in Phonkeo and Saensi) would be flooded while the upper elevation gardens would be arable for the growing season. In the simulation, the year following the wet year is the most impacted, so farmers could plan accordingly and not plant crops at the lower-elevation gardens. Moreover, these gardens would be flooded during the planting time and would become exposed as the growing season progressed. Thus, while farmers may lose income the year after a flood because of lost vegetable revenues, they would not have invested in planting yet, so the risk of flooding would not be great.

Table 6 shows the average generation of power at the THXP power plant overall and for the wet and dry seasons, for the baseline, 425Apr, and 425Mar models. Fig. 7 shows the impact of this reduced storage on the power production during the driest months. The recession agriculture rules 425Apr and 425Mar reduce the production of power at a broad range of levels in May. Rule 425Mar also creates reductions across the spectrum of power production in April. Neither rule has a significant impact on power production during the third driest month, June, nor do the rules impact the nine wettest months (not shown).

An hourly model was simulated to identify the hours and days of the week most likely to be impacted by the garden rule. The daily and hourly baseline models simulate the same water level in the NG reservoir (regression coefficient = 1.001). In the hourly 425Mar

Table 5. Percent Reduction in Exposure during Highest Magnitude Flood (1996) and Following Year, Compared to Average Exposure for Each Model

Year	Baseline (%)	A1 (%)	A2 (%)
1996	0	2	3
1997	16	11	5

Table 6. Average Production of Power (MW) at THXP Plant for Baseline, 425Apr, and 425Mar

Season	Baseline	425Apr	425Mar
Overall	335	325	308
Dry	299	284	254
Wet	385	383	383

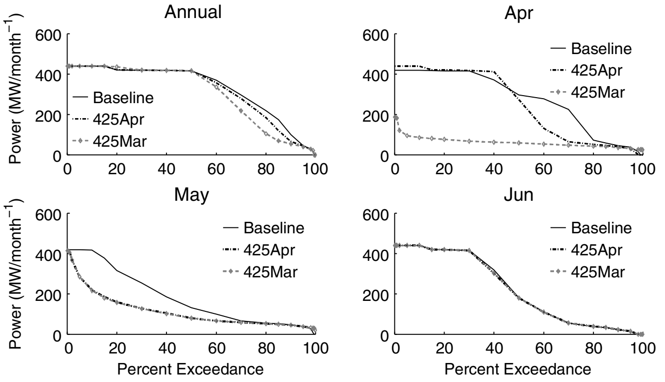

Fig. 7. Daily percent exceedence curves for baseline and rules 425Apr and 425Mar for annual and dry months, April–June

simulation, the water level is able to stay near the full supply level of the THXP reservoir most days of the year. The median power generation for the hourly baseline and 425Mar models exceeds the demand, as shown in Figs. 8 and 9, because excess water must be released because of storage limitations in the THXP reservoir. While the hourly baseline can meet the peak demand 90% of the hours (Figs. 8 and 9), the hourly garden rule 425Mar falls short of the peak demand more than 25% of the time. The total reduction in power for the hourly garden rule is 8.1% compared to the baseline hourly model. The months of shortage from the hourly demand for the garden rule are April–June. The weekend demand is not fully met for 10% of days. The production is nearly zero for the minimum of days simulated for both baseline and garden scenarios.

The daily model that simulates an average daily demand equivalent to the peak demand, 86 m^3/s, was evaluated to see whether it could be used as a proxy for the hourly peaking model during the months most impacted by the garden rules. However, the daily model does not show the elevation of the THXP rebounding during off-peak hours, thus diminishing the power generation. As such, the power capacity at the THXP dam, as predicted by the daily model, appears to be more limited than in the equivalent hourly peaking model described previously.

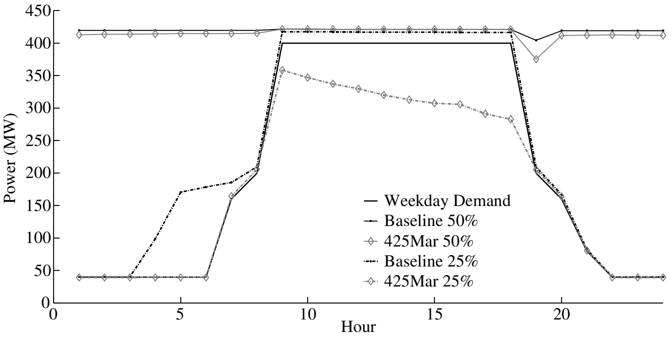

Fig. 8. Median and lower quartile of power production of hourly baseline compared to weekday demand

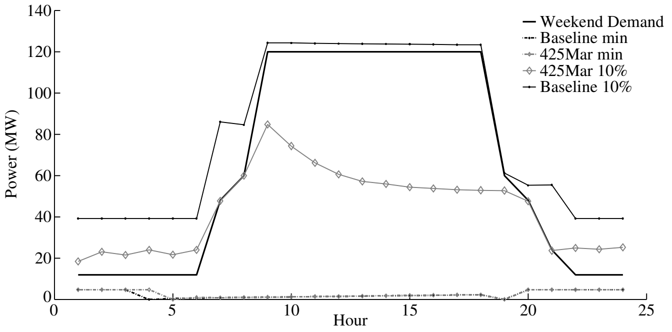

Fig. 9. Weekend demand (dashed line) compared to baseline and 425Mar low production (10% and minimum)

When flood control is not integrated into the dam operation rules, the simulations show a possibility of flooding downstream of the NG dam. Large outflows do occur more frequently from the gardening rules (Fig. 10). Except for a 1996 flood event, the flows were maintained below the maximum release of 500 m^3/s throughout the 25-year simulation (Fig. 11). When applied to the baseline, 425Apr, and 425Mar, the restricted release MaxQ reduced the average power generated by less than 1 MW for each alternative and did not reduce at all the area of land exposed.

For agricultural targets, the water level was drawn down to 430 and 435 m, creating the alternatives 430Apr, 430Mar, 435Apr, and 435Mar, and modification of the rules 425Apr and 425Mar led to a smaller power reduction and, in some cases, a greater amount of land exposed (E) (Fig. 12). Compared with 425Apr, the alternative 435Mar, which drew down the water level to 435 m from March through August, exposed 1.0% more land while also generating slightly more power.

Discussion and Conclusions

Although in the hourly peaking model the energy demand was met 75% of the time, the hourly model simulated a reduced hydropower demand, which may underestimate the potential power loss. While the purpose of simulating the hourly model for this study was to approximate the hydropower impact of the agricultural rules for

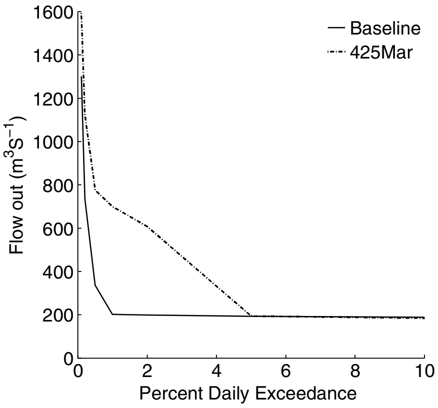

Fig. 10. Large flows out of NG reservoir with baseline and 425Mar

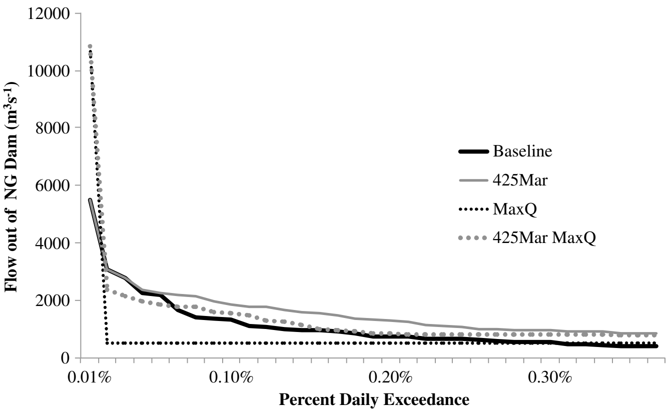

Fig. 11. Highest flows out of NG Dam for baseline and 425Mar model, with and without maximum flow rules (MaxQ)

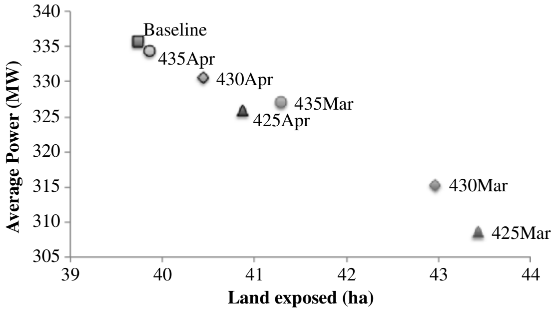

Fig. 12. Average power (MW) and land exposed E (ha), for each alternative simulated

hourly operation, the actual hourly schedule used by the THPC would need to accurately gauge the impact on power generation.

The steep geometry of the NG basin limits the potential for recession agriculture because an incremental drop in water level exposes less land than it would in a shallow basin. Thus, compared to a shallower basin, the depth of drawdown must be proportionally greater to expose each unit area of shoreline, leading to a larger decrease in hydropower generation per unit area of land exposed. The modest success in meeting both targets of hydropower generation and shoreline gardening points to the potential for integrating shoreline gardening goals into dam operation in more favorable locations.

One potential concern with the gardening operation rule is that large releases are made to quickly draw down the water level to expose the gardens. While there was no maximum release control criteria specified by the power company, the gardening rule, with releases that are routinely in excess of 200 m^3/s, could possibly cause flooding. While the maximum flow rule had no impact on exposure of gardening area, it caused larger releases during very high flooding events as compared with the baseline. Flood forecasting and a graduated maximum release that increases with storage levels (and forecasted inflows) could help to avoid reservoir spills or damaging downstream flows. Additional research is needed to determine channel capacities or maximum discharges that do increase flood risk above acceptable levels.

This study considered whether certain elevations were more important than others for shoreline gardening, so that the gardening operation rule could specify this threshold as a target. Because the area of land suitable for shoreline gardening increases incrementally between 425 and 430 m, rules drawing the water to higher elevations were just as effective at exposing potential gardening area as the rule drawing the water level to 425 m, as originally proposed. While the alternative 435Mar with 435 m maximum water level and longer growing season increased the power generation and exposure (E) compared with 425Apr, when selecting a gardening measure, one could also weigh the economic value that could be derived from having more land available for a shorter period (e.g., 425Apr) of time versus less land available for a longer period of time (e.g., 435Mar). Further, hydropower operators could provide farmers the expected water level schedule over the coming year to help farmers plan their gardens, as discussed in the methods and as practiced in Yali Reservoir, Vietnam (Toan et al. 2013).

The price of electricity may help the owners of the NG dam and other decision makers evaluate the true cost of the loss in hydropower. The price of electricity is negotiated at the beginning of each year, so the cost of hydropower losses due to the agriculture rules could be determined each year. When comparing the benefits of hydroelectric power against farming livelihoods, economic metrics could be used. Economic factors include the amount of net cash gain achieved and the number of people benefiting from each target. While a detailed economic assessment is beyond the scope of this paper, simple calculations indicate that the gross economic gain from hydropower is much greater than from shoreline gardens. The median value of hydropower generated during the growing season (March–August) for the baseline simulation is worth between US $450,000 and US$12 million, before operating costs, which were not obtained for this study (Electricite du Laos 2012). The revenue earned depends on whether electricity is sold to the government of Lao PDR or to foreign companies. The net gain of the harvested crops is between US$7,000 and US$13,000, assuming a net gain of US$256/ha of shoreline garden (Joffre 2011), depending on the maximum distance to gardens allowed and the water-level rule that is used. Nonetheless, the personal gain of the displaced villagers belies this simple economic comparison. In fact, it is this disparity in profits that has so often led to the omission of consideration of impacts on local livelihoods. Local communities affected by hydropower development, such as the resettlement community in Keosenkham, need to be provided with suitable alternative livelihood opportunities that are sustainable in the long term.

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