# APPENDIX C1

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# Assessing competing policies at Ubonratana reservoir, Thailand

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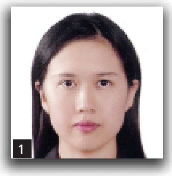

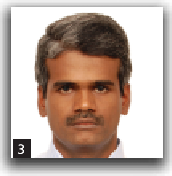


**As the main water resources infrastructure in the region, the Ubonratana reservoir has played and continues to play a significant role in the socio-economic well-being of north-eastern Thailand. For such a multi-purpose system serving flood protection and various water demand needs, it is important that the reservoir is effectively operated to ensure that the overall performance of the system is enhanced. Consequently, this study has evaluated the performance of the Ubonratana reservoir with four competing operating policies, namely: (*a*) the pre-2002 policy (P1); (*b*) a post-2002 policy, following the catastrophic flood of 2002 (P2); (*c*) a policy derived in the current study to address the limitations of P2 in relation to water shortages (P3); and (*d*) the standard operating policy, SOP (P4). The simulation analyses were implemented using a water evaluation and planning system model of the reservoir meeting domestic (first priority), industrial (second priority), irrigation (third priority) and in-stream (fourth priority) needs. The performance was summarised in terms of reliability, vulnerability, resilience and sustainability. The results showed that overall, P4 was the best, followed by P3, P1 and P2 in that order. This is a useful demonstration of how rule curves can successfully guide the operation of multi-purpose reservoir systems.**

## Notation

| | |
|---|---|
| $A_t$ | exposed surface area of reservoir at time $t$ |
| $D_t$ | water demand during period $t$ |
| $D'_t$ | actual water release from reservoir during period $t$ |
| $e_t$ | depth of net evaporation loss during time $t$ |
| $f_d$ | total duration of failures |
| $f_s$ | number of continuous sequences of failure periods |
| $\mathrm{LRC}_t$ | lower rule curve ordinate at $t$ |
| $j$ | index for user category |
| $L_t$ | seepage losses from reservoir during period $t$ |
| $M$ | total number of user categories |
| Max. WL | maximum water level in reservoir |
| $\mathrm{Mm}^3$ | million cubic metres |
| Min. WL | minimum water level in reservoir |
| $N$ | total number of time periods in simulation |
| $N_s$ | number of time periods demand was met |
| $Q_t$ | inflow to reservoir during time $t$ |
| $R_t$ | reliability (time-based) |
| $R_v$ | reliability (volumetric-based) |
| $S_t$ | reservoir storage at beginning of period $t$ |
| $\mathrm{URC}_t$ | upper control curve ordinate at $t$ |
| $w_j$ | weight factor for user category $j$ |
| $\eta$ | vulnerability |
| $\lambda$ | sustainability |
| $\lambda_G$ | group sustainability |
| $\phi$ | resilience |

## 1. Introduction

Reservoir operation is concerned with allocating the available water in a reservoir in a way that maximises the overall performance of the reservoir. Reservoirs are commonly sized on the basis of historical runoff and other data, but whatever the intentions at the planning stage in relation to the reliability and other metrics of performance of the system, there is no guarantee that the prevailing hydro-meteorological conditions during the operation of the reservoir will achieve the set out intentions. This is why the operational control of reservoirs becomes critical to ensure that allocation of the available water is done in such a way that results in overall optimisation of the system's performance.

The derivation of reservoir operating policies has engaged water resources researchers for a long time and analyses have involved the use of various optimisation schemes and water scarcity-related objective functions (see Hashimoto *et al.*, 1982; ReVelle *et al.*, 1969; Shiau, 2009; Shih and ReVelle, 1995; Yeh, 1985). At the other extreme is the use of the standard operating policy (SOP) that relies on supplying the demand if sufficient water is available, but if not to supply all the available water and leave the reservoir empty (Hashimoto *et al.*, 1982). The SOP is very easy to use and can be shown to maximise the overall volumetric reliability of the reservoir system; however, because it does not attempt to redistribute water in a way that protects periods of extreme low flows, its vulnerability (or maximum single period shortage) can be very high if the reservoir encounters an extremely dry period during its operation, as explained by Adeloye *et al.* (2001).

Several investigators (Srinivasan and Philipose, 1996; Taghian *et al.*, 2013) have researched ways of improving the performance of the SOP by attempting to develop a system of water hedging so that water can be held back during the period of relative wetness to meet some of the demands during the periods of extreme low flows. Although this is a welcome development, however, significant uncertainty remains as to the timing and quantity of the hedging (Shiau, 2009). Consequently, the SOP was applied in its basic form in this study without any hedging consideration.

The above and other problems associated with formalised reservoir operating policies including the SOP have led most reservoir operators to rely on the use of heuristic rule curves to guide reservoir operation. Rule curves give target levels that must be maintained in a reservoir at various periods in order to meet the demand over the drawdown–refill cycle of the reservoir. Unlike the operating policies, rule curves can be derived using simulation studies of the reservoir; specifically the modified sequent peak algorithm (see Adeloye *et al.*, 2001; McMahon and Adeloye, 2005), which is immune from the misbehaviour of traditional behaviour analysis, could be used.

Figure 1 shows the pre-2002 rule curves at Ubonratana, which can be used to illustrate how rule curves help in guiding reservoir operation. Traditionally, there is only one curve, the upper rule curve (B) in Figure 1, which is below the reservoir top water level (A) and must be kept this way to accommodate possible flood surcharges. If the reservoir level is at or above the rule curve, then the demanded water or possibly more must be released to restore the storage to the level dictated by curve (B). If the storage is below the rule curve (B), however, restriction in the volume of water supplied is warranted. The latter situation is the main problem with the rule curve: while it might indicate when reductions in the amount of water supplied are warranted, it does not provide guidance as to the quantity of the reduction. Adeloye *et al.* (2003) derived rule curves with integrated hedging policy using the modified sequent peak algorithm (Adeloye *et al.*, 2001) as a way of removing the limitations of traditional rule curves. Another solution that has been widely adopted is to complement the upper rule curve (B) with a lower rule curve (C),

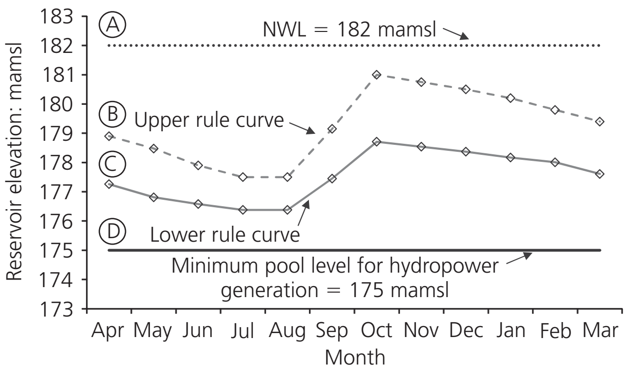


**Figure 1.** Pre-2002 rule curves for reservoir operation at Ubonratan reservoir (mamsl: metres above mean sea level; NWL: normal water level in reservior)

with the proviso that when the reservoir level is within the space enclosed by the two curves, full demand could be met. The upper rule curve (B) thus defines the maximum level for flood control purposes and the lower curve (C) defines the limit for conservation purposes, and the objective of the operation is to restore reservoir level to the lower curve (C) by reducing the supplied water or to the upper rule curve (B) by over-supplying the demand. Ideally, the water in the buffer zone (between curve (C) and the minimum pool level (D) prescribed for hydropower generation) should also go into supply, albeit at a reduced rate, to improve the overall performance with respect to the water supply functions, but this is not done at Ubonratana.

The multi-purpose Ubonratana reservoir in north-eastern Thailand has been operated for a long time using rule curves in Figure 1 to meet municipal (domestic and industrial), irrigation, in-stream and hydropower water needs (EGAT, 2002). All the water available for the consumptive uses first passes through the turbines for power generation before being allocated. When water is insufficient, the available water is prioritised among these needs, with the municipal water supply having the highest priority followed by the others in the order mentioned in a winner-takes-all fashion. In other words, an attempt is first made to satisfy the domestic water demand in full if possible after which, if there is water left, attention turns to the second priority user and so on.

However, in 2002, because of a severe flood that devastated the region, a revised set of rule curves were derived essentially involving the lowering of the upper rule curve of the existing rules to accommodate more flood water. While this resulted in reducing the flooding impacts, however, it worsened the ability of the reservoir to meet the water demand needs, especially during extremely low flow periods. To improve the situation with regard to water supply performance, a further improvement of the post-2002 rule curves was attempted in the current study, resulting in new upper and lower rule curves that are everywhere below their post-2002 counterparts. Thus, the water available for allocation under the newly derived rule curves would both improve overall water supply performance and at the same time reserve a more generous space for flood water in comparison with the post-2002 policy.

Although the above might be the case, it is still important to test objectively how superior the newly derived rule curves are, relative to the previously used curves at Ubonratana. Additionally, as the lower rule curve for the newly derived policy lies on the minimum pool level on occasions and while this might mean that more water will be available for conservation, operating the reservoir so close to the minimum level might be risky, especially if an unusually dry spell is encountered during operation which may cause the reservoir to fail catastrophically in its water supply function. Maintaining the storage level above the minimum pool level is also critical for hydropower generation at Ubonratana. Ascertaining the likelihood or probability of the reservoir storage level ever reaching the minimum pool level, especially when operated with the new rule curves, is therefore also important.

Thus, the aim of this study is to investigate the performance of the Ubonratana reservoir when guided by the pre-2002 rule curves (P1), the post-2002 rule curves (P2), the newly derived rule curves in this study (P3) and the SOP (P4). The analysis used reservoir behaviour simulation which was implemented in the water evaluation and planning (WEAP) system (Sieber and Purkey, 2011). Following simulation in the WEAP, reservoir performance was then evaluated in terms of reliability (time- and volume-based), resilience, vulnerability and sustainability indices (Adeloye, 2012). In the next section, further details about the methodology are given. This is then followed by a description of the details of the case study, including the data and their associated analyses. The results are then presented and discussed, followed by the final conclusions.

## 2. Methodology

### 2.1 Reservoir simulation

Reservoir simulation in WEAP uses the mass balance equation of the inflows and outflows for the reservoir as follows

$$S_{t+1} = S_t + Q_t - D'_t - e_t A_t - L_t;$$
$$\text{LRC}_t \leqslant S_{t+1} \leqslant \text{URC}_t \qquad (1)$$

where $S_{t+1}$, $S_t$ are the contents of the storage at times $t + 1$ and $t$, respectively, $Q_t$ is the inflow to the storage during time $t$, $D'_t$ is the release in volume units during time $t$, $e_t$ is the depth of net evaporation (i.e. evaporation – rainfall) loss during time $t$, $A_t$ is the exposed surface area of the reservoir at time $t$, $L_t$ is the seepage loss in volume units during time $t$, $\text{URC}_t$ is the upper rule curve at $t$ and $\text{LRC}_t$ is the lower rule curve at $t$. In general, as illustrated in Figure 1, the rule curves are defined for each calendar month and remain static. The constraint on the right-hand side of Equation 1 limits the reservoir content within the boundary of $\text{URC}_t$ and $\text{LRC}_t$; consequently, when this constraint is to be violated, $D'_t$ will be increased or reduced as appropriate to restore reservoir content to within this boundary.

In Equation 1, net evaporation (i.e. evaporation – rainfall) loss is included explicitly in volume units, but in WEAP the net evaporation depth is used directly to adjust reservoir elevation obtained by way of the storage-elevation function, which must be provided. A similar approach was suggested by Montaseri and Adeloye (2004). Other losses ($L_t$) due to seepage, etc. are ignored. At the end of the simulation, various performance indices as outlined in the following section are evaluated. As noted by Adeloye *et al.* (2001), using behaviour simulation in performance evaluation as described above does not suffer from the misbehaviour of the method once identified by Pretto *et al.* (1997).

### 2.2 Evaluated performance indices

A reservoir is said to perform satisfactorily if it meets the demand in all time periods; when this is not the case, there is a performance failure. Reservoir performance is traditionally characterised by the reliability, vulnerability, resilience and sustainability (McMahon *et al.*, 2006).

#### 2.2.1 Reliability

The reliability concept can be applied in either the time or volume domain. In the time domain, reliability ($R_t$) is the proportion of the total time under consideration in which a reservoir will be able to meet the demand without shortage, namely

$$R_t = \frac{N_s}{N} \qquad (2)$$

where $N_s$ is the total number of intervals out of $N$ that the demand was met. In the volumetric domain, reliability ($R_v$) is the total quantity of water actually supplied divided by the total quantity of water demanded during the entire operational period

$$R_v = \frac{\sum_{t=1}^{N} D'_t}{\sum_{t=1}^{N} D_t} \qquad (3)$$

where $D'_t$ is the actual release from the reservoir system during period $t$ and $D_t$ is the demand during the same period. It should be noted that $D'_t$ ignores excess releases, that is, if $D'_t > D_t$, it is set to $D_t$ for the purpose of evaluating Equation 3. If the demand is satisfied in all the time periods, then $R_t = R_v = 1$; however, in general for any system, $R_v \geqslant R_t$.

#### 2.2.2 Resilience
Resilience is a measure of the reservoir's ability to recover from failure and the most widely used definition of resilience is attributable to Hashimoto *et al.* (1982)

$$\phi = \frac{1}{(f_\mathrm{d}/f_\mathrm{s})} = \frac{f_\mathrm{s}}{f_\mathrm{d}}; \quad 0 < \phi \leqslant 1 \tag{4}$$

where $\phi$ is resilience, $f_\mathrm{s}$ is the number of continuous sequences of failure periods and $f_\mathrm{d}$ is the total duration of the failures, that is $f_\mathrm{d} = N - N_\mathrm{s}$.

#### 2.2.3 Vulnerability
The definition of vulnerability used here is attributable to Sandoval-Solis *et al.* (2011) and is the average period shortfall as a ratio of the average period demand, namely

$$\eta = \frac{\sum_{t=1}^{f_\mathrm{d}} [(D_t - D_t')/D_t]}{f_\mathrm{d}}; \quad t \in f_\mathrm{d} \tag{5}$$

where $\eta$ is vulnerability (dimensionless) and all other terms are as defined previously.

#### 2.2.4 Sustainability
A sustainability index that integrates the three earlier defined indices was first proposed by Loucks (1997) as

$$\lambda = R_\mathrm{t}\phi(1-\eta) \tag{6}$$

where $\lambda$ is the sustainability. However, this implicitly gives too much weight to the worst index; for example, if any of the indices $R_\mathrm{t}$, $\phi$ and $(1-\eta)$ is very low, the resulting $\lambda$ will also be very low. The extreme case is what could be termed the 'nullity' problem, in which if any of the constituent indices is zero, $\lambda$ will also be zero, irrespective of the values of the remaining indices. A modification of Equation 6 was recently proposed by Sandoval-Solis *et al.* (2011), which partially overcomes this problem by using the geometric mean as follows

$$\lambda = [R_\mathrm{t}\phi(1-\eta)]^{1/3} \tag{7}$$

Although Equation 7 does not resolve the nullity problem of Equation 6, it is nonetheless more versatile, flexible and can better reflect the effect on $\lambda$ of changes in the constituent indices. More specifically, the scaling represented by using the geometric mean in Equation 7 means that the worst index does not bear too heavily on the estimated sustainability index.

The sustainability can be evaluated for each of the users' categories or sectors (i.e. domestic, industrial, irrigation, etc.) and then combined to obtain the group sustainability index for the entire water resources system

$$\lambda_\mathrm{G} = \sum_{j=1}^{M} w_j\lambda_j \tag{8}$$

where $\lambda_\mathrm{G}$ is the group sustainability, $\lambda_j$ is the sustainability for users' category $j$, $w_j$ is the weighting for user $j$ and $M$ is the total number of users' categories. A simple way of specifying the weighting is to use the proportion of the total system average annual demand that is represented by each users' category (Sandoval-Solis *et al.*, 2011), that is

$$w_j = \frac{D^j}{\sum_{j=1}^{M} D^j} \tag{9}$$

where $D^j$ is the average annual water demand for users' category $j$.

## 3. Analyses

### 3.1 Case study
The case study is the Ubonratana dam reservoir in the upper Chi River basin in north-eastern Thailand. This is a single, multi-purpose reservoir for water supply (domestic, industrial, irrigation, in-stream flow needs), hydropower generation and flood control. The dam is located on Pong River at Phong Neap, Ubonratana district in Khon Kaen province, between latitudes 16° and 17°30′ N and longitudes 101°15″ and 102°45″ E (Figure 2(a)). The dam height is 36 m, with a length of 885 m (including the 100 m spillway) and a width of 6 m at the top. The dam was completed in 1966 and started operation in 1970. Other details of the dam and its reservoir are summarised in Table 1.

A schematic diagram of the reservoir and the various diversions is shown in Figure 2(b). The water requirements are released through two main canals above the Nong Wai weir and this released water first passes through the hydropower turbines to generate electricity, before being allocated to the respective needs. The average annual water demand per sector is summarised in Table 1, which shows clearly that water demand by the Nong Wai irrigation project accounts for the lion's share, namely >75%, of the total annual demand. The side flow at the Nong Wai irrigation diversion weir effectively helps in modulating any irrigation water shortages that result from the dam's release.

### 3.2 Data
Data collected for the study included daily runoff inflow, evaporation, area–height–storage relationship, water demand data and operational records of the reservoir. The reservoir inflow data spanned 1970–2011 and were provided by the

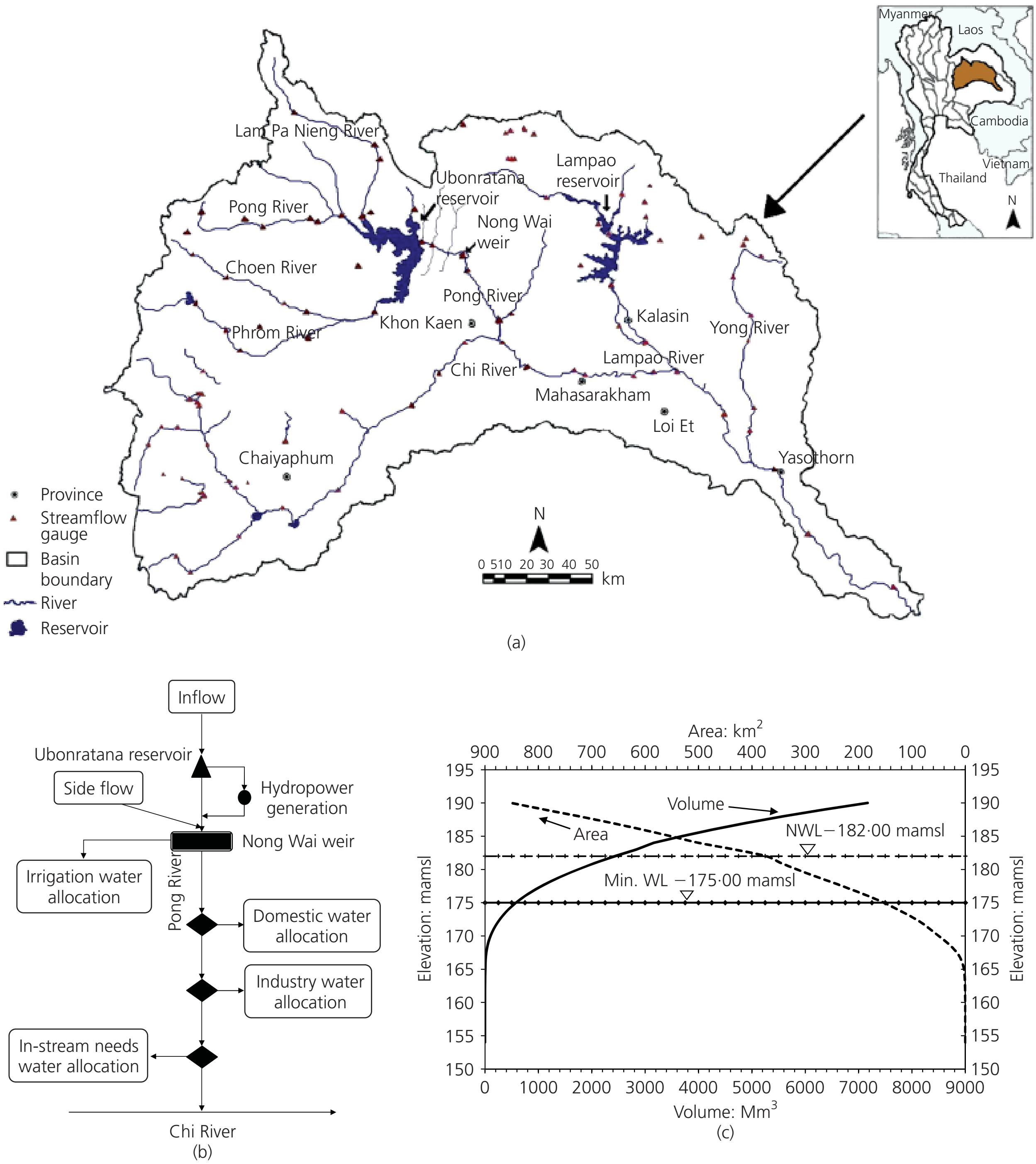


Figure 2. Study location showing: (a) map of Thailand, Chi River and the Mun River basins (Meethom, 2011); (b) schematic diagram of reservoir and the various diversions; (c) the reservoir elevation–area–storage relationship

Electricity Generating Authority of Thailand (EGAT), the dam's operators. The inflows were not measured directly but were estimated by EGAT using mass balance considerations (EGAT, personal communication). The mean annual inflow in Table 1 includes the runoff and direct rainfall on the reservoir surface, but not the average yearly direct evaporation of 540 $Mm^3$. Similarly, the mean annual release of 1834 $Mm^3$ excludes the mean annual spills of 229 $Mm^3$. Irrigation is the responsibility of the Royal Irrigation Department (RID) and they provide EGAT with estimates of the irrigation water requirements and

| Hydrological data | | Reservoir physical data | |
|---|---|---|---|
| Catchment area: km$^2$ | 12 000 | Total reservoir capacity: Mm$^3$ | 2431 |
| Nong Wai irrigation project: km$^2$ | 411 | Active storage: Mm$^3$ | 2311 |
| Other irrigation: km$^2$ | 28 | Storage at min. WL for hydropower: Mm$^3$ | 581 |
| Mean annual rainfall: mm | 1200 | | |
| Mean annual evaporation: mm | 1175 | Dead storage: Mm$^3$ | 120 |
| Mean annual evaporation: Mm$^3$ | 541 | Max. WL: mamsl | 186 |
| Mean annual inflow including rainfall: Mm$^3$ | 2604 | | |
| Mean annual release: Mm$^3$ | 1834 | NWL: mamsl | 182 |
| Mean annual spills: Mm$^3$ | 229 | | |
| Mean annual water requirement: Mm$^3$; ratio of total | (803; 1) | Min. WL for hydropower: mamsl | 175 |
| Municipal demand | (49; 0·06) | Dead storage level: mamsl | 168 |
| Industrial demand | (29; 0·04) | | |
| Irrigation | (599; 0·75) | | |
| In-stream needs | (126; 0·16) | | |

**Table 1.** General data of the Ubonratana reservoir (the means relate to April 1970–November 2011)

water allocation plan for the Nong Wai project. Gauging of the tributary at Nong Wai weir was only started in 2002; however, EGAT had estimated the pre-2002 tributary flows using a rainfall–runoff approach in combination with a water balance accounting of the record of releases and abstractions from the Ubonratana reservoir. The elevation–area–storage relationship is shown in Figure 2(c). This was surveyed in 2002 but was assumed to be valid for the entire simulation period. As noted previously, Figure 2(c) was used for incorporating evaporation loss in the simulation.

### 3.3 Operating policies

The tested policies for Ubonratana were

(*a*) the policy practised before 2002 (P1)
(*b*) the policy practised after 2002 (P2)
(*c*) the policy derived in this study (P3)
(*d*) the SOP (P4).

The rule curves are summarised in Table 2 and Figure 3 affords a graphical comparison of the three policies. P3 was developed from P2 using a trial-and-error procedure involving progressively shifting downward its URC and LRC (thus making available some of the buffer zone water for supply) and observing the resulting water shortage relative to P2. A similar procedure was proposed by Jiang (2011) and, as shown in Figure 3, the resulting P3 policy is in general wider than P2 (implying that more water will be supplied towards meeting the various demand), does not violate the minimum pool level for hydropower generation, and its upper rule curve (URC) is everywhere below the corresponding curve for P2, thus improving flood protection relative to P2. For the SOP (P4), the URC is the reservoir capacity and the lower rule curve (LRC) was set at 175 mamsl, the minimum pool level for hydropower generation.

## 4. Results and discussion

The simulation analysis was implemented in WEAP on a monthly basis. Monthly demands for domestic, industrial and in-stream needs were based on constant daily rates of 0·134, 0·078 and 0·345 Mm$^3$, respectively. Irrigation demand was seasonal, with a wet season (June–October) monthly demand of 62·52 Mm$^3$ and a dry season (November–May) monthly demand of 41·0 Mm$^3$. The difference is due to the cultivation of a much larger area (36 000 ha) of paddy rice in the wet season when compared with the dry season cultivation of 13 000 ha.

The total unmet annual demand for each of the policies during the shortage years is shown in Figure 4. As can be seen, P2 recorded the highest shortfall, followed by P1 and P3 in that order. For example, while the total unmet demand for P2 was 1909 Mm$^3$, the corresponding values for P1 and P3 were 671 and 364 Mm$^3$, respectively. As noted previously, P2 was meant to redress the flooding difficulties by restricting the active storage capacity; it is therefore not surprising that the conservation performance of the reservoir has significantly deteriorated as a consequence of adopting P2. The SOP did not record any shortfall at all in Figure 4, which is not surprising given that the SOP is meant to maximise the period's volumetric reliability (Hashimoto *et al.*, 1982). However, the SOP could also produce high vulnerability; that is, single period shortage, if it occurs, could be excessive, but there was no such occurrence in the current study because by default all the water above the minimum hydropower pool level of 175 mamsl, which is much larger than the space enclosed between the URC and LRC of any of P1–P3, is available for meeting demands with the SOP.

The performance indices are summarised in Table 3. In general, the volume-based reliability was always higher than the time-based reliability, as expected, which is why caution should be

| Policy | Rule curve | Rule curve ordinates: Mm³ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar |
| P1 | URC | 1412·76 | 1298·69 | 1151·43 | 1056·58 | 1056·58 | 1483·58 | 2071·33 | 1985·63 | 1901·83 | 1803·82 | 1677·57 | 1556·52 |
| | LRC | 1002·29 | 905·68 | 858·86 | 819·52 | 819·52 | 1045·11 | 1360·39 | 1314·60 | 1269·84 | 1218·51 | 1178·49 | 1082·11 |
| P2 | URC | 1371·31 | 1176·02 | 1000·07 | 848·44 | 945·65 | 1483·58 | 2071·33 | 2071·33 | 2071·33 | 1901·83 | 1740·05 | 1556·52 |
| | LRC | 1002·29 | 868·89 | 796·53 | 719·59 | 772·13 | 1040·54 | 1360·39 | 1360·39 | 1360·39 | 1269·84 | 1185·92 | 1082·11 |
| P3 | URC | 1371·31 | 1127·39 | 945·65 | 796·53 | 905·68 | 1440·83 | 1901·83 | 1901·83 | 1901·83 | 1819·96 | 1740·05 | 1556·52 |
| | LRC | 842·97 | 748·26 | 661·25 | 581·67 | 620·55 | 661·25 | 868·89 | 868·89 | 868·89 | 796·53 | 772·13 | 748·26 |

**Table 2.** Ordinates of rule curves tested

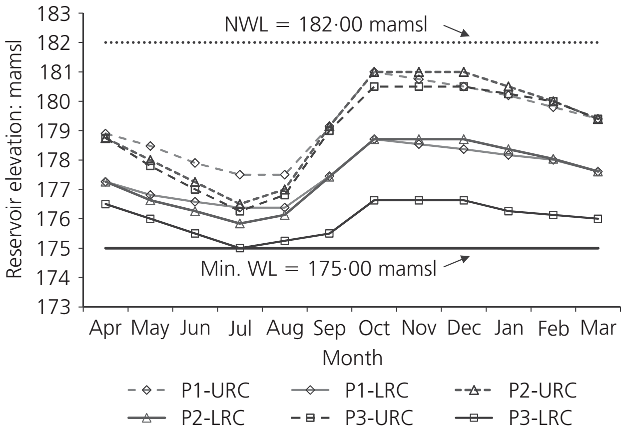


**Figure 3.** The tested rule curves at Ubonratana

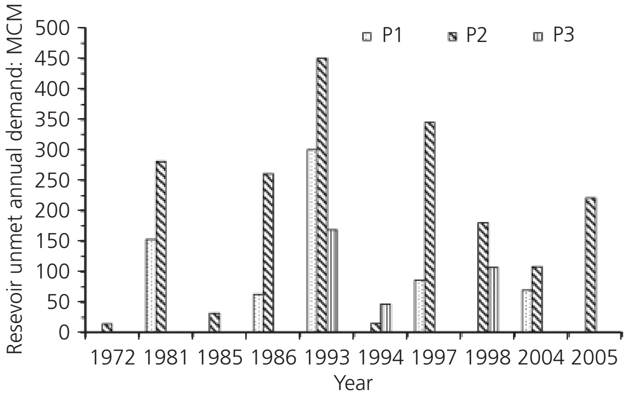


**Figure 4.** The unmet annual demand in the failure years of the simulation period (1970–2011)

exercised when adopting the time-based reliability for system evaluation: the fact that time-based reliability is low does not make the water supply situation of the system poor. As noted by Adeloye (2012), while the initial evaluation of systems performance can be based on the time-based reliability $R_t$ because it is simple to estimate and might be readily recognised by users who are already familiar with the concept of return periods, the volumetric reliability should also be evaluated and any necessary adjustments made to the system's characteristics in the light of this. For example, the $R_t$ may be relaxed (or reduced), such as through increasing the release from the reservoir to meet additional needs or adopting a lower reservoir capacity during planning, if the $R_v$ is very high. The volumetric reliability estimates in Table 3 fully support the observation made earlier regarding the relative sizes of the unmet demand by each of the policies. Additionally, the volumetric reliability tends to decrease as the sectoral priority decreases; this is also as expected. As the SOP did not produce shortages, the resilience $\phi$ (Equation 4) is undefined and the three reliability measures attained; their respective ultimate values as expected; that is, $R_v = R_t = 1$; $\eta = 0{\cdot}0$.

| Policy/water user | Mean annual demand | Reliability: % | | $\phi$ | $\eta$ | $\lambda$ | $\lambda_G$ |
|---|---|---|---|---|---|---|---|
| | | $R_t$ | $R_v$ | | | | |
| P1 | | | | | | | |
| Domestic | 49 | 96·34 | 99·45 | 0·50 | 0·6745 | 0·54 | 0·50 |
| Industry | 29 | 98·98 | 99·12 | 0·40 | 0·8689 | 0·37 | |
| Irrigation | 599 | 96·54 | 97·99 | 0·35 | 0·5804 | 0·52 | |
| In-stream needs | 126 | 99·19 | 96·94 | 0·33 | 0·8368 | 0·38 | |
| P2 | | | | | | | |
| Domestic | 49 | 97·15 | 98·22 | 0·43 | 0·6241 | 0·54 | 0·32 |
| Industry | 29 | 96·34 | 96·80 | 0·44 | 0·8757 | 0·38 | |
| Irrigation | 599 | 93·09 | 93·94 | 0·26 | 0·8774 | 0·31 | |
| In-stream needs | 126 | 92·89 | 93·32 | 0·26 | 0·9396 | 0·24 | |
| P3 | | | | | | | |
| Domestic | 49 | 99·39 | 99·65 | 1·00 | 0·5758 | 0·75 | 0·53 |
| Industry | 29 | 99·19 | 99·33 | 1·00 | 0·8197 | 0·56 | |
| Irrigation | 599 | 98·37 | 98·92 | 0·50 | 0·6622 | 0·55 | |
| In-stream needs | 126 | 98·17 | 98·35 | 0·44 | 0·9017 | 0·35 | |
| SOP | | | | | | | |
| Domestic | 49 | 100·00 | 100·00 | – | 0·0000 | 1·00* | 1·00 |
| Industry | 29 | 100·00 | 100·00 | – | 0·0000 | 1·00* | |
| Irrigation | 599 | 100·00 | 100·00 | – | 0·0000 | 1·00* | |
| In-stream needs | 126 | 100·00 | 100·00 | – | 0·0000 | 1·00* | |

* Based on two indices: $R_t$ and $\eta$ – only.

**Table 3.** Summary of evaluated reservoir performance indices for the tested policies

The estimated sustainability indices using Equation 7 for each user category are shown in the penultimate column of Table 3, while the group sustainability is shown in the last column. For the SOP, $\lambda$ was computed using only $R_t$ and $\eta$. In terms of sustainability, P2 is clearly inferior to P1 and this further confirms the water supply difficulty that had attended the introduction of P2. However, the newly developed policy P3 is marginally better than P1 and much better than P2 in terms of the group sustainability index. The superiority of the P3 relative to both P1 and P2 is exemplified by the sustainability index for the domestic and industrial water supply sectors, where P3 offers a system that is almost 40% more sustainable than either P1 or P2. Consequently, P3 has improved the performance of Ubonratana significantly in relation to its highest priority functions, namely, domestic and industrial water supply. However, as remarked previously, the reservoir is a multi-purpose system relied upon for flood protection in addition to its conservation needs; consequently efforts such as P3 to improve the water supply performance should not be at the expense of the flood protection function. This is why in developing P3 it was ensured that its upper boundary was everywhere below the upper boundary for P2 (Figure 3). Consequently, although P3 has significantly improved the water supply performance relative to P2, its flood protection function should be similar, if not better than that of P2. As expected, the sustainability index for the SOP was unity throughout.

To further test the robustness of P3, especially in relation to the simulated reservoir storage ever reaching the minimum pool level prescribed for hydropower generation, a statistical analysis of the annual minimum storage levels was carried out. To do this, the minimum storage level in each year of the simulation was extracted to form a series. This gave an annual minimum storage series of 41, the number of years of the simulation record. These were then ranked from smallest to highest and probabilities were assigned based on the Weibull plotting position. The resulting probability plot is shown in Figure 5, where it can be seen that the probability of attaining the minimum pool level (581 $Mm^3$) is below 1%.

Finally, although performance with regard to hydropower generation was not the main concern of this study, an attempt was made to estimate the hydropower equivalent of the water passing through the turbines that actually went into meeting the various consumptive and in-stream demands. For example, for a typical generation efficiency of 80% (see McMahon, 1993), the average power equivalent of the water released for meeting the demands with policies P1 to P4 were, respectively 2636, 2576, 2728 and

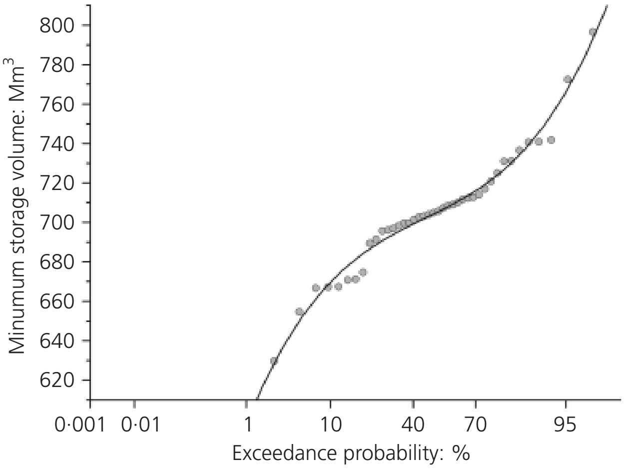


**Figure 5.** Empirical cumulative distribution function for annual minimum reservoir storage at Ubonratana

3190 kW. These are much lower than the 25·2 MW installed capacity at Ubonratana because, as shown in Table 1, not all the water passing through the turbines (annual average = 1834 $Mm^3$) is required to meet the demands (annual average = 803 $Mm^3$). The slight variations in the hydropower equivalents of the water supplied towards the demands are in broad agreement with the total amount of water released (and the estimated volumetric reliability, $R_v$ (Table 3) under each policy.

## 5. Conclusion

This study has examined three operational strategies for the multi-purpose Ubonratana reservoir in north-eastern Thailand. Using a reservoir for both flood control and conservation (water supply, irrigation, in-stream) purposes creates problems for operation because, whereas the former requires the reservoir to be as empty as possible, the latter requires a reservoir that is, for most times, full so that it can meet the demands with an acceptable level of performance. The initial set of rule curves (P1) used for the operation of the Ubonratana prior to 2002 performed the water supply function satisfactorily but failed on flooding. The post-2002 rules (P2) that replaced them reduced the flooding problem but aggravated water shortage. This study has developed a new set of rule curves (P3) that has remedied the post-2002 water shortage problem but should not affect the post-2002 level of protection against flooding offered by Ubonratana. The performance of the three operating policies along with the SOP in meeting water demands was compared using the sustainability index, which was evaluated for each of four user categories, namely domestic, industrial, irrigation and in-stream needs, and for an aggregation of the categories. While the SOP was the best for water supply, it is strictly not a realistic option for reservoir operation when flood control is a consideration because reservoir storage can attain the maximum full capacity level with the SOP, with little or no space left in the reservoir for accommodating flood water. Of the three heuristic rules evaluated, the sustainability results showed that P3 was better than both P1 and P2, for the individual categories as well as their aggregation. Although the lower rule curve for P3 was much lower than its P1 and P2 counterparts, statistical analysis carried out to establish the probability of reservoir storage ever reaching the minimum pool level with P3 showed that this is very low. This is a significant outcome because maintaining water above the minimum pool level at Ubonratana is important to guarantee adequate hydropower generation. Finally, based on the limited consideration of hydropower generation in the study, P3 appears to be the best of the non-SOP policies. The better hydropower generation performance of the SOP (P4) relative to the others is to be expected but, as noted before, this would likely be at the expense of the additional flood protection that policies P1–P3 offer.

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