

Assessing water management alternatives in a multipurpose reservoir cascade system in Sri Lanka

Thushara De Silva M.^{a,b,*}, George M. Hornberger^{a,b,c}

^a Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN, USA

^b Vanderbilt Institute for Energy and Environment, Vanderbilt University, Nashville, TN, USA

^c Department of Earth and Environmental Sciences, Vanderbilt University, Nashville, TN, USA

ARTICLE INFO

Keywords:

Mahaweli reservoir cascade
Hydropower
Irrigated agriculture
Reliability
Resilience
Vulnerability

ABSTRACT

Study region: The Mahaweli multipurpose water resources system of Sri Lanka, spread across 25,500 km², incorporates the Mahaweli, Kala Oya, Malwatu Oya, Kantale Oya and Maduru Oya river basins.

Study focus: We developed a model that can be used to assess water resources management alternatives of reservoir cascade operation to fulfill diverse and often conflicting water demands. The Mahaweli project is mainly operated for hydropower generation and irrigated agriculture. This study quantifies performances of water management alternatives considering trade-offs between hydropower and agricultural yield. Reliability, resilience, and vulnerability are other considerations that we explore.

New hydrological insights for the region: In the Mahaweli reservoir system, water is used primarily for paddy irrigation and hydropower generation. Increasing water diversions for paddy irrigation leads to decreases in hydropower so in times of limited water availability, decisions about trade-offs are required. In addition to diversions, decisions about how much arable land to cultivate during times of water shortage affect measures of risk related to paddy yield. Our results show that existing infrastructure places a constraint on how much water diverted for irrigation can be used productively and also leads to spatial variability in improvements in risk measures at the expense of reductions in expected yield across the basin.

1. Introduction

Multipurpose reservoir cascades are managed to fulfill diverse and often conflicting water demands to as great an extent as possible. These projects are operated for hydropower generation, drinking water supply, tourism, irrigation, flood regulation, and navigation. The spatial and temporal diversity of water users and the limited availability of water in some seasons require that trade-offs be made in response to demands of the multiple water users. For example, if water managers keep reservoir water levels low during a wet period to meet flood protection goals, there may not be enough water to meet agricultural water demands in a subsequent dry period. One particularly important trade-off for developing countries is between hydropower and irrigation (Digna et al., 2018; Räsänen et al., 2015; Tilmant et al., 2009). If water is transferred from upstream reservoirs for irrigation, downstream hydropower generation is penalized. On the other hand, if the water is taken from storage to run turbines to produce electricity during low irrigation water demand, water may not be available later to be used for irrigation.

* Corresponding author at: Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN, USA.
E-mail address: thushara.k.de.silva@ieee.org (T. De Silva M.).

Choices about how to operate a reservoir system will depend on how different aspects of performance are valued. The economic value of products such as hydropower generation and agricultural goods is a measure of system performance (Sakthivadivel and Molden, 1999). Evaluating trade-offs between hydropower and agriculture can involve non-economic preferences as well. For example, if agriculture is set as a priority, elevating the fraction of water delivered to agricultural fields may be a goal.

Maximizing system performance measures is the main operational goal for cascades, but minimizing risks of failure is also a management goal. Evaluation of water allocation options in a cascade system requires an assessment of the reliability, resilience, and vulnerability to variable and uncertain basin inflows (Huizar et al., 2018; Jain and Bhunya, 2008; Mateus and Tullós, 2016; Saha et al., 2017; Srdjevic and Srdjevic, 2017; Zhang et al., 2017). Since Hashimoto et al. (1982) proposed the use of reliability, resilience and vulnerability indices as performance measures of water resources systems, these indices have been used extensively for informing decisions in reservoir system planning and management. (Ajami et al; Jain 2010).

Water resources must be simulated to estimate the evaluation metrics for water management alternatives. Complex models (e.g. RIBASIM, WEAP, MIKE BASIN, MODSIM, WBalMo and HEC-ResSim) have been used in detailed studies of reservoir cascade systems (Loucks, 2005; Loucks and van Beek, 2017; US Army Corps of Engineers, 2013; Vieira et al., 2018) but these approaches may not be necessary for initial assessments. One powerful approach particularly useful at a screening level is a system dynamics approach (Jahandideh-Tehrani et al., 2014). A system dynamics simulation of reservoir cascade operation reflects a simplified flow diagram with water balance equations used to calculate the reservoir storages and releases under a set of operating rules (Sharifi et al., 2013). Conceptual simulation models based on water balance relationship have been used for reservoir operation evaluation of multiple river basins (Kling et al., 2014; Tinoco et al., 2016).

The Mahaweli multipurpose water resources system of Sri Lanka furnishes water for irrigated agriculture and hydropower generation, supplying about 20% of the annual irrigation water demand and 20% of the electrical energy demand of the country. Water managers need to balance diversion of Mahaweli water to irrigation districts at the upstream end of the basin with downstream releases for hydropower generation and smaller irrigated agricultural systems. Specifically, Mahaweli water managers must consider spatial and temporal variability of hydrology across the cascade system, limitations of installed infrastructure, and trade-offs among competing demands of hydropower and agriculture.

The objective of this study is to develop a relatively simple model to evaluate the performance of various water resources allocations in meeting the hydropower and irrigation water demands for the Mahaweli multipurpose water resources system of Sri Lanka. We develop a modular simulation model based on water balance principles for the Mahaweli reservoir cascade, which can be used to screen water allocation alternatives through overall system performance judged by hydropower generated, paddy yield, the fraction of water delivered to agriculture, and a set of indices that describe the reliability, resilience and vulnerability of the system.

2. Description of reservoir cascade

The Mahaweli multipurpose project of Sri Lanka (Fig. 1) is spread across 25,500 km² and is operated mainly for hydropower generation and irrigated agriculture.

Seven major reservoirs of the Mahaweli project are associated with hydropower plants with 815 MW capacity (Fig. 2). Downstream of these major hydropower reservoirs water is delivered to four irrigation systems (A, B, C, and E). There are seven water distribution points where water allocations are managed. The main diversion at Polgolla currently is limited by rule to 875 Mm³ annually, although the diversion tunnel has the capacity to transfer 1400 Mm³ per year. The diversion at Polgolla supports hydropower plants with 78 MW and paddy farming with a capacity of 95,000 ha. Distribution points send water to ten agricultural systems. The agricultural systems are named using capital letters (Fig. 1). Our overall system model includes the full complement of reservoirs, diversions, and distribution points (Fig. 2). To provide clarity, we selected five representative irrigation systems to illustrate the results from our model for the Mahaweli complex. Two of the systems (B and C) are fed from the undiverted water used by upstream power plants of the Mahaweli (Fig. 3). The other three systems (D1, D2 and H) represent areas fed by water diverted first at Polgolla and then at a set of distribution points. System D1 and H are served by a number of small local irrigation reservoirs (tanks) whereas System D2 is fed by one irrigation tank (Fig. 2).

Mahaweli system irrigation water for agriculture systems in paddy production is planned considering the monsoon rainfall pattern (Fig. 4). The crop water requirement for each system is varied throughout the two agricultural seasons: “Yala” (April–September) and “Maha” (October–March), which are based on the northeast monsoon (NEM) and the southwest monsoon (SWM) that bring rain to the country. Crop water requirements of Mahaweli agricultural systems vary spatially according to the soil type and soil moisture content (Mahaweli Authority of Sri Lanka, 2017). All the agricultural systems of the dry zone of the country benefit from the second intermonsoon (October–November) and the northeast monsoon (December–February) during the Maha season and irrigation water requirements are less for the Maha season than for the Yala season.

We use data on power production for each dam, information about water requirements for agriculture systems (Fig. 4), and 63 years of data on the system hydrology (i.e., inflows to the reservoirs) to calculate the hydropower and paddy production. There are two growing seasons in each year so there are 126 seasons in the historical record to explore how the hydropower and irrigation systems perform for various water allocation options.

3. Methods

We develop a simulation model for the Mahaweli multipurpose project of Sri Lanka to evaluate water resource management alternatives to supply irrigation and hydropower demands. The simulation model represents the major components of the system –

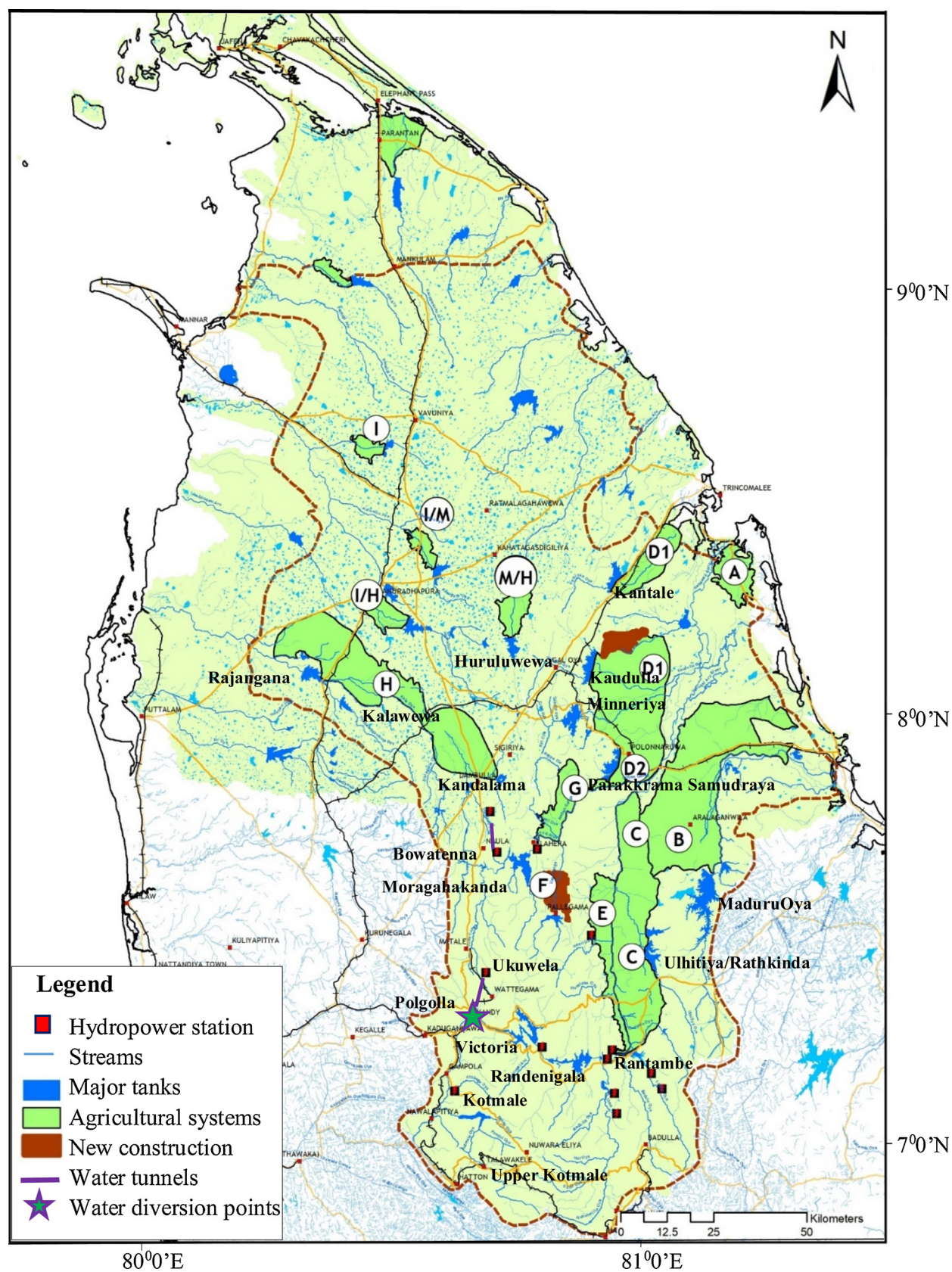


Fig. 1. Mahaweli multipurpose project reservoirs, stream network and irrigated agricultural systems (A,B,C,D1,D2,E,G,H,I/H and MH).

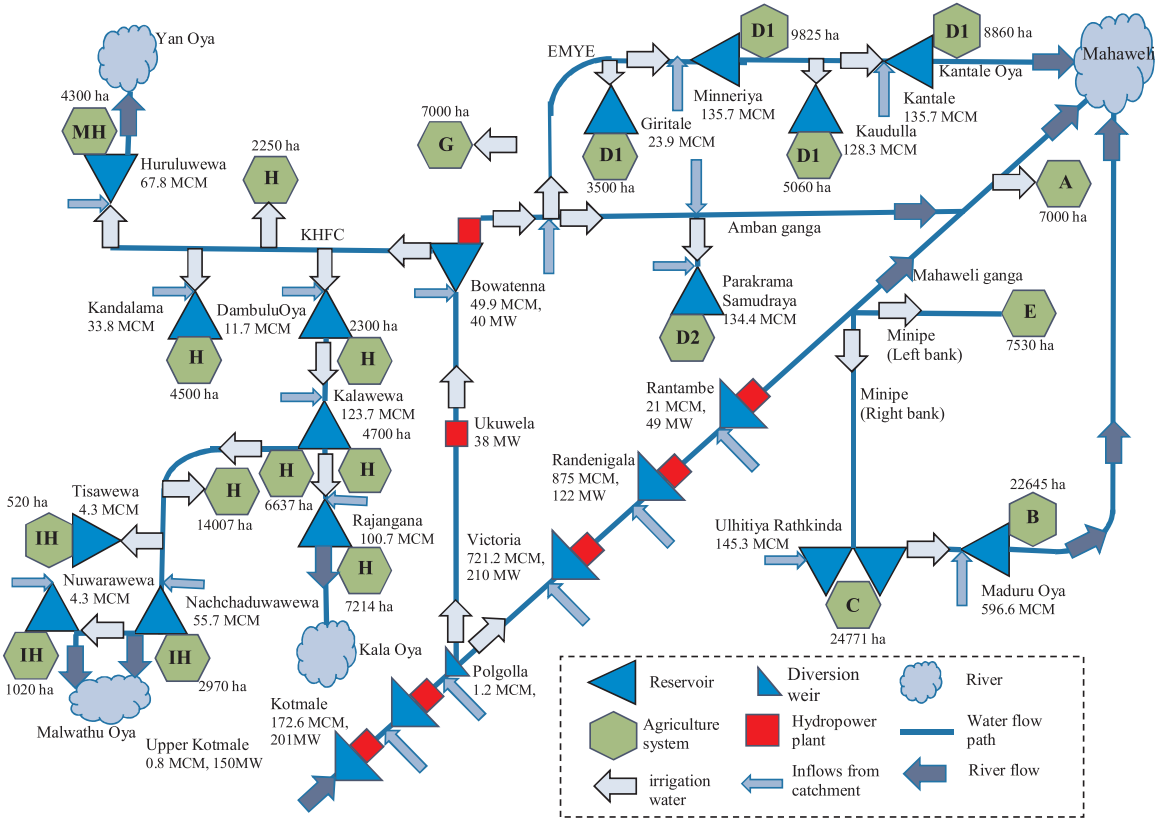


Fig. 2. Schematic diagram of Mahaweli multipurpose water resources project.

reservoirs, agricultural systems, and hydropower plants. Operational rules for reservoir water releases and water diversions are incorporated.

3.1. Simulation model

The reservoir simulation model is developed in the MATLAB/ SIMULINK platform.

3.1.1. Reservoir

Consider N reservoirs in the cascade system. Reservoir operation for the i^{th} reservoir is represented through the water mass balance equation (Eq.(1)).

$$S_i(t) = S_i(t-1) + LI_i(t) + Q_{i-1}(t) - E_i(t) - Q_i(t) - Sp_i(t) \quad (1)$$

Reservoir storage ($S_i(t)$) is calculated by adding local inflows ($LI_i(t)$) and upstream reservoir discharges ($Q_{i-1}(t)$) and by subtracting evaporation ($E_i(t)$), spill ($Sp_i(t)$), and reservoir discharge ($Q_i(t)$) (Eq. (1)). Reservoir spill ($Sp_i(t)$) is a positive value when the total water ($T_i(t)$) in a reservoir is greater than the reservoir capacity (S_{max}) and otherwise is zero (Fig. 5). Reservoir area ($A_i(t)$) and elevation ($H_i(t)$) are calculated from the reservoir characteristics curves. Reservoir discharge ($Q_i(t)$) at each time step is determined according to the reservoir operation rules.

Reservoir discharge ($Q_i(t)$) is determined from: (1) a reservoir guide curve ($RC_i(t)$), (2) the water requirements ($R_{Mi}(t)$) for hydropower and/or agricultural purposes (reservoirs are operated for both purposes or one purpose), (3) the current reservoir storage, and (4) the minimum reservoir operating level (S_{min}) using Eqs. (2)–(5). Division by six in Eq. (3) is to reflect the need to supply water for the entire agricultural season, which lasts for six months.

Managing the reservoir cascade according to the composite storage volumes in all reservoirs to develop rule curves for individual reservoir releases is a way to achieve an overall optimal policy. However, due to calculation complexities and spatial differences in hydrometeorology and irrigation demands, Mahaweli system reservoir cascade rule curves have been developed individually. The reservoir rule curves are based on the rainfall pattern of the catchment, temporal variation of irrigation water demands, and individual reservoir parameters.

$$S_i(t) < S_{min}, Q_i(t) = 0 \quad (2)$$

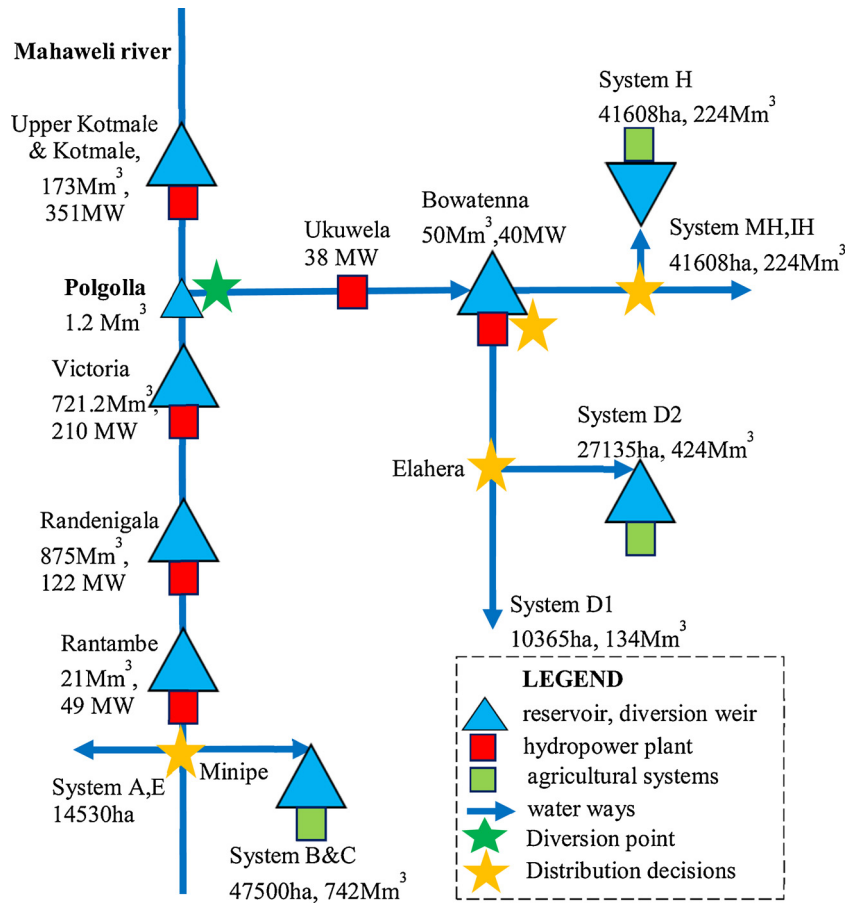


Fig. 3. Schematic diagram of Mahaweli hydropower plants and agriculture systems B, C, D2 and H.

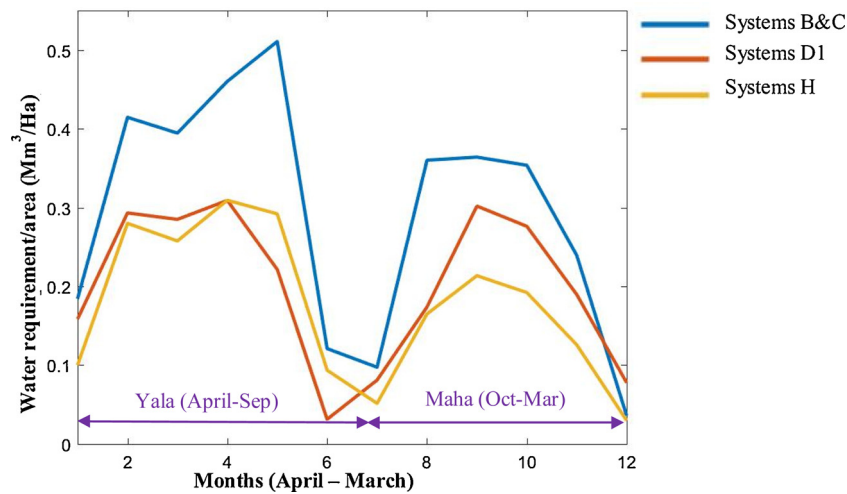


Fig. 4. Crop water duty cycle for system B&C, D1, H for two agriculture seasons 'Yala' and 'Maha'.

$$S_{min} < S_i(t) < RC_i(t), Q_i(t) = (S_i(t) - S_{min})/6 \quad (3)$$

$$S_i(t) > RC_i(t) \text{ but } R_{Mi}(t) > (S_i(t) - RC_i(t)), Q_i(t) = S_i(t) - RC_i(t) \quad (4)$$

$$R_{Mi}(t) < (S_i(t) - RC_i(t)), Q_i(t) = R_{Mi}(t) \quad (5)$$

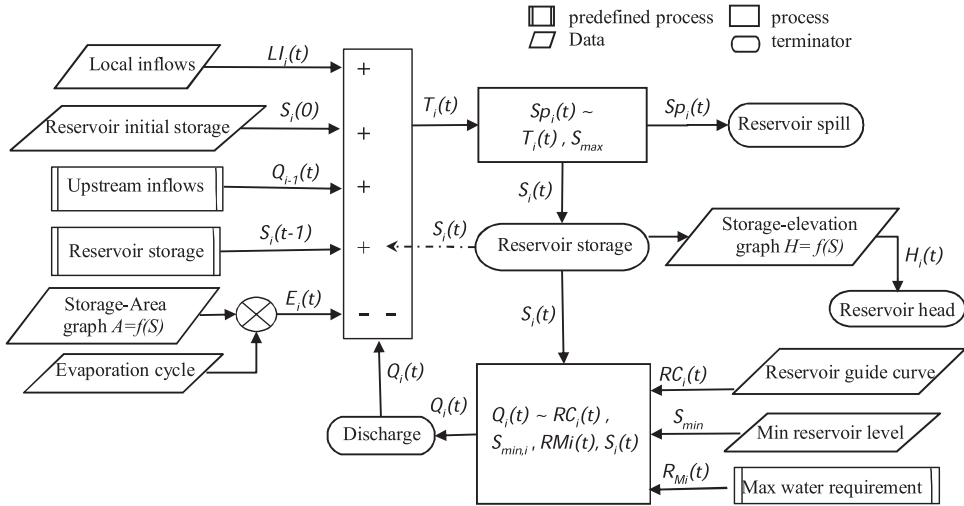


Fig. 5. Reservoir operation simulation.

3.1.2. Hydropower plant

Hydropower production is a function of efficiency ($\eta_i(t)$), density of water (ρ), acceleration due to gravity (g), effective head ($H_i(t)$) and discharge ($Q_i(t)$) (Eq. (6)). Reservoir head varies according to the reservoir water level. Efficiency ($\eta_i(t)$) is a function of both effective head and discharge (Fig. 6).

$$P_i(t) = \eta_i(t) \rho g H_i(t) Q_i(t) \quad (6)$$

Hydropower energy production is the product of power and time. The maximum value of energy is constrained by the total power plant capacity. At each time step, the plant factor is calculated. If the plant factor is less than one, energy is calculated using Eq. (6). Otherwise energy is calculated from the total plant capacity.

3.1.3. Agricultural systems

Water is distributed to a number (n) of agricultural systems. The success of meeting agricultural water demands in the i^{th} agricultural system is measured by comparing irrigation water availability ($I_{ri}(t)$) and the water requirement for agricultural crops ($D_{ti}(t)$) (Fig. 7). Crop water requirement or water duty ($D_i(t)$) varies during the cycle from land preparation to harvesting. In addition, the crop water requirement varies spatially according to the soil type and soil moisture content (Rivera et al., 2018). The total water requirement ($D_{ti}(t)$) is a product of water duty ($D_i(t)$), water requirement per unit area (Mm^3/Ha) (Fig. 4), and harvested land ($A_i(t)$) from the total land available in the system. We calculate the fraction ($U_i(t)$) where total water demand ($D_{ti}(t)$) is met from available irrigation water ($I_{ri}(t)$). A water demand threshold $MT_i(t) = x\%$ of total arable land is specified and used to decide the success or failure of the agricultural season. If $U_i(t) > MT_i(t)$, the season is taken to be successful. Water managers can specify the water demand threshold taking into account water thresholds of irrigation systems, in essence defining success by cutting back on the area irrigated when water is scarce. For this study we specify the threshold as 90% for each time period.

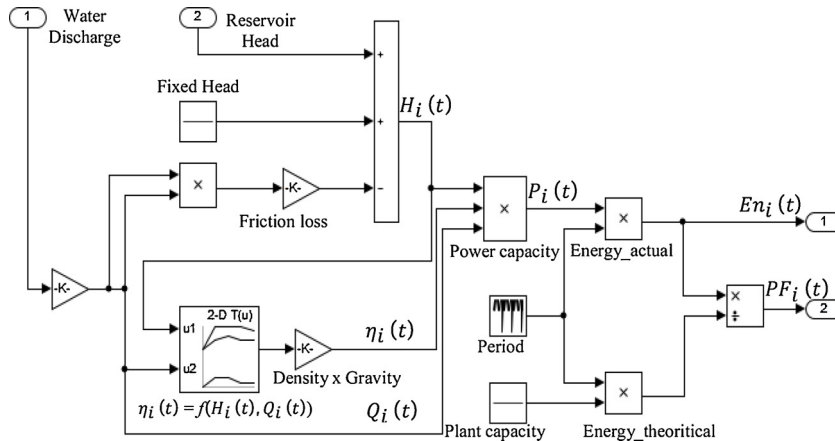


Fig. 6. Hydropower plant simulation.

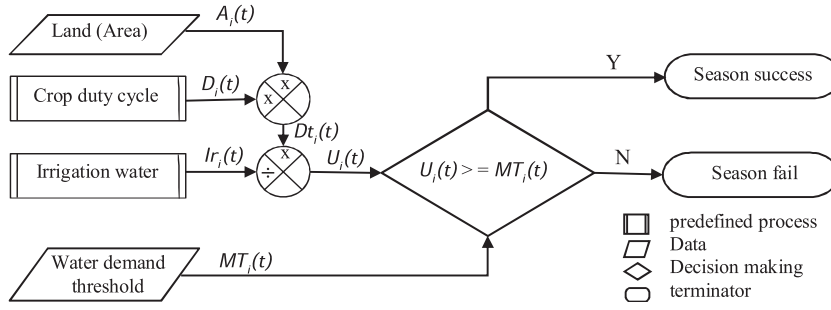


Fig. 7. Agriculture system simulation.

3.1.4. Water distribution decision

Irrigation water from upstream reservoirs is distributed in two steps to the smaller irrigation tanks (Fig. 8). First, maximum possible quantities ($Ir1_i(t)$) are distributed among the systems, considering the total irrigation water ($I(t)$) availability and the water requirement ($Dt_i(t)$) of each agricultural system (Eq.(7)). Then, if the remaining water in upstream reservoirs is higher than the upstream reservoir capacity (S_{max}), additional water ($Ir2_i(t)$) is distributed among the downstream irrigation tanks according to the availability of space in each tank ($C_i(t)$)(Eq.(8)). If there is no space in the downstream irrigation tanks, additional water is spilled (Eq.(1)). Some agricultural systems have a dedicated irrigation tank to serve the local system while some others do not. For these systems irrigation water requirement ($Dt_i(t)$) from upstream reservoirs is the deficit not served by local tanks. For other systems, it is the total water requirement for cultivation. In Eqs. (7) and (8), n is the number of agricultural systems served by the upstream reservoirs.

$$Ir1_i(t) = \begin{cases} I(t) \frac{Dt_i(t)}{\sum_{i=1}^n Dt_i(t)}, & I(t) \leq \sum_{i=1}^n Dt_i(t) \\ Dt_i(t), & I(t) > \sum_{i=1}^n Dt_i(t) \end{cases} \quad (7)$$

$$Ir2_i(t) = \begin{cases} \left[I(t) - \sum_{i=1}^n Ir1_i(t) \right] \frac{C_i(t)}{\sum_{i=1}^n C_i(t)}, & I(t) > \sum_{i=1}^n Ir1_i(t) \text{ and } I(t) - \sum_{i=1}^n Ir1_i(t) \leq \sum_{i=1}^n C_i(t) \\ C_i(t), & I(t) > \sum_{i=1}^n Ir1_i(t) \text{ and } I(t) - \sum_{i=1}^n Ir1_i(t) > \sum_{i=1}^n C_i(t) \\ 0, & I(t) \leq \sum_{i=1}^n Ir1_i(t) \end{cases} \quad (8)$$

3.2. Project performance measurements

The performance of water management decisions is assessed using three measures: (1) products (agricultural products and electricity generated); (2) reliability, resilience, and vulnerability indices; and (3) the fraction of water delivered to irrigated fields.

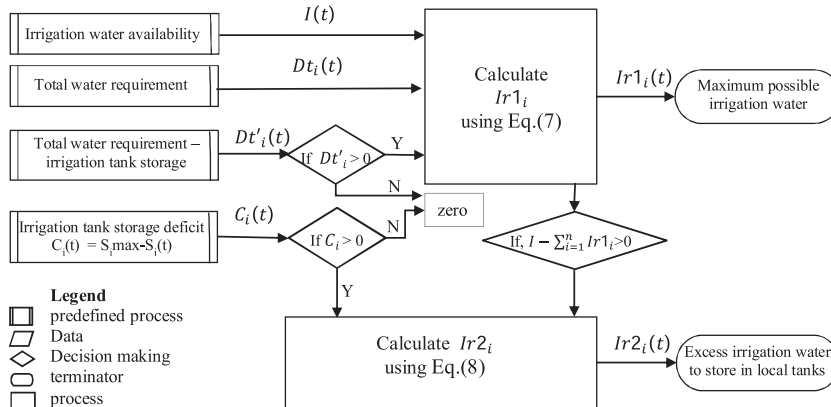


Fig. 8. Irrigation water distribution decision.

Table 1

Measure of success for hydropower and irrigation performance.

Water user	Success measure
Hydropower	Power production for the season equals or exceeds the 15-year (2002–2017) average for the season
Irrigation	90% of the crop water requirement for 4 months of the season is provided for 90% of land available for irrigation

3.2.1. Products of water users

Crop yield for agriculture and electricity produced from hydropower are taken as measures of production. Although the monetary value of electricity typically is higher than the monetary value of crops, agricultural systems are associated with high employment opportunities and the social value is very high.

3.2.2. Reliability, resilience, and vulnerability

Reliability, resilience, and vulnerability indices are used to evaluate the performances of hydropower plants and agricultural systems (Ajami et al., 2008; Hashimoto et al., 1982; Loucks and van Beek, 2017). Reliability is a measure of success of meeting water demands and resilience is a measure of recovering from a failure. Vulnerability measures the severity of failure (Jain and Bhunya, 2008; Sandoval-solis et al., 2011; Zhang et al., 2017). The indices are calculated for each agricultural season in recognition of the way decisions for water allocation are made. For this study, the system is simulated using a monthly time step. Success or failure is identified by setting a threshold for the partial fulfillment of the demands for hydropower and agricultural systems for the seasons (Table 1). In Section 3.1.3 (Fig. 7), we estimate the success or failure of agricultural systems for each month and convert this data into the success of the six month season using the threshold. We use satisfaction of a minimum of four months water requirement as a season success (S_i). Since we haven't taken into account all the local inflows to the agricultural systems, and studying past seasonal data for 2002–2017 (Mahaweli Authority of Sri Lanka, 2017) we assume partial fulfillment as a success of season rather than requiring fulfillment of all six months water demands from irrigation water. We use the 2002–2017 average as our threshold measure for hydropower (Table 1) since data for hydropower production are not available for all 63 years of the record. To be consistent, we use only energy data for hydropower plants operated throughout the 15 years for calculating the average value. Although there is no absolute reason for selecting the average as a threshold, we consider it useful for comparison of hydropower reliability, resilience and vulnerability values for different water allocation options.

The success or failure of a season ($V(t)$) is measured as $X(t)$, where the state is set as one for success and zero for failure (Eq. (9)) (Hashimoto et al., 1982; Mondal and Wasimi, 2007; Zhang et al., 2017).

$$X(t) = \begin{cases} 1, & \text{if } V(t) \text{ success} \\ 0, & \text{if } V(t) \text{ fail} \end{cases} \quad (9)$$

Reliability is a measure of the number of successful seasons over the total number of seasons (T) considered for the simulation (Eq. (10)) (Hashimoto et al., 1982; Mondal and Wasimi, 2007; Zhang et al., 2017).

$$\text{Reliability} = \frac{\sum_{t=1}^T X(t)}{T} \quad (10)$$

Transition from failure to the next state is measured by $W(t)$, where success is set as one and failure is set as zero (Eq. (11)).

$$W(t) = \begin{cases} 1, & \text{if } X(t) = 0 \text{ and } X(t-1) = 1 \\ 0, & \text{if } X(t) = 0 \text{ and } X(t-1) = 0 \end{cases} \quad (11)$$

Resilience is a measure of how quickly a system is likely to recover after a failure (Chanda, 2014; Hashimoto et al., 1982; Mondal and Wasimi, 2007; Simonovic and Arunkumar, 2016). We estimate the ratio of total recoveries from failure to success from the total number of failures during the simulation (Eq.(12)).

$$\text{Resilience} = \frac{\sum_{t=1}^T W(t)}{T - \sum_{t=1}^T X(t)} \quad (12)$$

Vulnerability is a measure of the severity of the failure (Ajami et al., 2008; Asefa et al., 2014; Fowler et al., 2003; Moy et al., 1986), which is measured as the maximum number of successive seasonal failures in this study (Eqs. (13) and (14)).

$$Y(t) = \begin{cases} 1 - X(t), & t = 1 \\ Y(t-1) + (1 - X(t)), & t > 1 \text{ and } X(t) = 0 \\ 0, & t > 1 \text{ and } X(t) = 1 \end{cases} \quad (13)$$

$$\text{Vulnerability} = \max_{t \in (1, \dots, T)} Y(t) \quad (14)$$

3.2.3. Fraction of water utilization for irrigation

The beneficial utilization of water for agriculture in the total system is estimated from total water inflows to the reservoirs, water releases for irrigation, and losses. Total water inflow (I) to the system is consumed by agricultural systems (Ir), is evaporated from the reservoir or tank (E), or is spilled (Sp) (Eq.(15)). Hydropower plants do not consume water so all water used for hydropower is available for irrigation in downstream areas. Water losses in waterways by evaporation and seepage, and water losses in the reservoirs by seepage are not considered for the water balance model. The share of water to the agricultural systems from the total is considered as the cascade's fractional agricultural utilization (Ef) in our study. We use cascade's fractional agricultural utilization as an indicator to measure the different water allocation options at the main water diversions of the water resources management. In our study, Polgolla is the main water diversion location and fractional utilization is considered only as a metric to compare options for this diversion.

$$\sum_{t=1}^T \sum_{i=1}^N I(t, i) = \sum_{t=1}^T \sum_{i=1}^M Ir(t, i) + \sum_{t=1}^T \sum_{i=1}^N [E(t, i) + Sp(t, i)]$$

$$Ef = \frac{\sum_{t=1}^T \sum_{i=1}^M Ir(t, i)}{\sum_{t=1}^T \sum_{i=1}^N I(t, i)} \quad (15)$$

3.3. Evaluation of water allocation alternatives of Mahaweli project

Several water allocation scenarios of Mahaweli reservoir cascade are analyzed using the simulation model. We examine two objectives associated with the agricultural systems: (1) risk indices for each system according to water management decisions and (2) fraction of land from the total arable lands that have 100% reliability according to the given water management decisions. Because one agricultural adaptation mechanism for seasons with very limited irrigation water available is to cultivate only a fraction of the arable land available, we also explore how performance varies considering planting decisions between 50% and 100% of the available land. We explore performance relative to management options of maintaining the current maximum diversion at Polgolla and of increasing the maximum diversion in steps up to 140% of the current value. Performance is measured in terms of: (1) reliability, resilience, and vulnerability (2) fraction of water used by irrigation systems, and (3) total agricultural crop yield and hydropower generation.

4. Results

For the present Polgolla water diversion policy, the irrigation systems show variable performance measures. System D2 shows the best reliability, resilience and vulnerability values. Systems B&C have higher reliability values than does system H, while system H shows higher resilience and lower vulnerability. (Table 2). The 15-year average hydropower production is met in 89 of the 126 seasons in the historical record.

The relative performance of the agricultural systems changes as the fraction of land cultivated decreases from 100% to 50% (Fig. 9). In particular, system H achieves the best performance indicators as the fraction of land irrigated decreases. Because water used for hydropower is available for irrigation downstream, hydropower does not affect results for irrigation in systems below the diversion at Polgolla; there is no influence for hydropower generation with variation of land fraction.

Reducing yields by decreasing the fraction of arable land cultivated from 100% to 50% results in improvements in risk performance measures (Fig.10). In systems B&C reducing yield from 400 kT to 300 kT increases reliability from 0.6 to 0.74 and increases resilience from 0.66 to 0.76. Patterns are similar for other systems, although in system H resilience improvements are minimal after yield is reduced by one third. (Note that the large yield values of system H and B&C compared to system D1 simply reflect a difference in total land area in each.)

Changing the water diversion policy at Polgolla has both positive and negative impacts (Fig. 11, Fig. 12). Performance of the system of hydropower plants and of irrigation systems B and C, which are on the main stem of the Mahaweli River below the diversion at Polgolla, become weaker with diversion of additional water to the northern area of the country and the performance of the irrigation systems supplied from the Polgolla diversion, D1 and H, become stronger (Fig. 11). As diversions at Polgolla increase, spills from the reservoirs off the main stem of the Mahaweli river increase, evaporation losses decrease, and the fraction of water supplied to irrigate lands first increases and then decreases (Fig. 12(a)). Diverting water from upstream to the north reduces the

Table 2
Performance measures of irrigation and hydropower systems.

Systems	Reliability	Resilience	Vulnerability	Land fraction meeting 100% reliability
System B&C	0.61	0.66	18	0.56
System D1	0.53	0.60	32	0.49
System D2	1.0	1.0	0	1.0
System H	0.57	0.71	13	0.45
Hydropower	0.71	0.57	8	

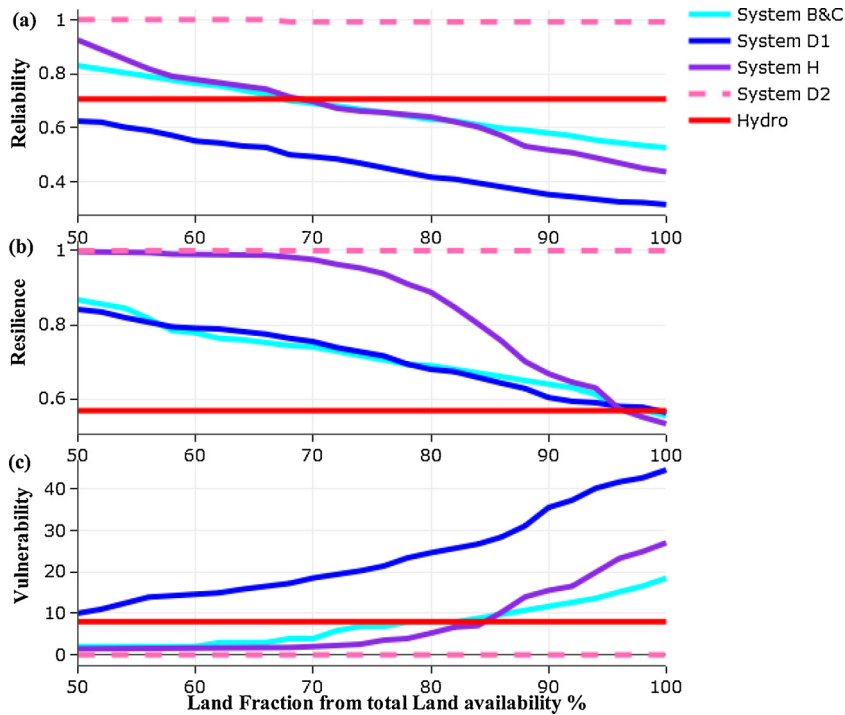


Fig. 9. Performances of agricultural systems and hydropower plants for the present water diversion policy for variable fraction of land cultivated in reliability, resilience and vulnerability measures. Note that hydropower is not affected because the diversion at Polgolla is fixed for these results.

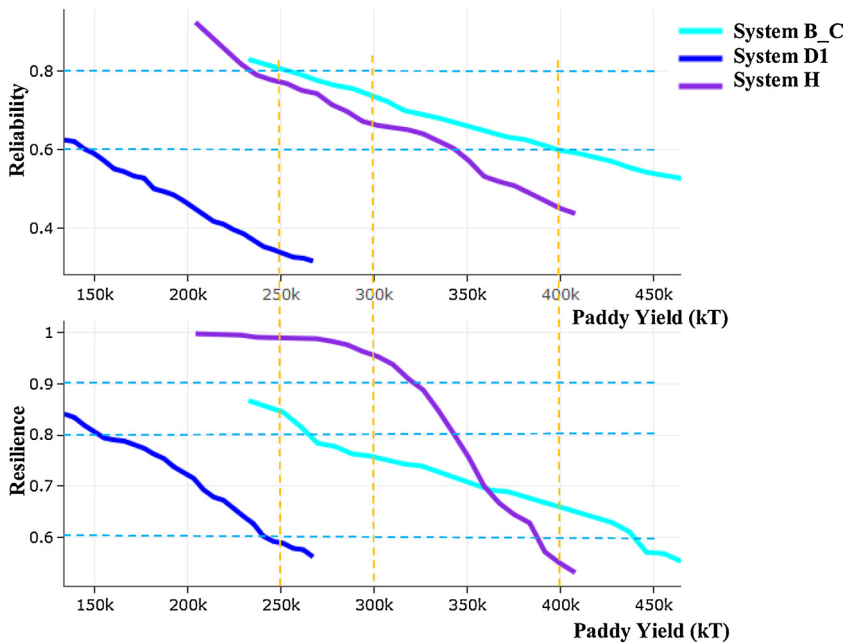


Fig. 10. Trade-offs between expected agricultural yield and reliability, resilience indices.

natural Mahaweli river flow; diversion has an essentially non-measurable impact on evaporation losses of downstream main reservoirs (Fig. 12(b)).

Water diversion at Polgolla involves a trade-off between irrigated agriculture and hydropower generation. Beyond a 16%, increase of the present water diversion at Polgolla there is no enhancement of either the paddy yield or energy production (Fig. 13). In fact, beyond a 16% increase, paddy yield actually decreases because systems on the main stem of the Mahaweli (e.g., B and C) receive less water and thus are less productive while at the same time systems to the north that receive water diverted at Polgolla (e.g., D1

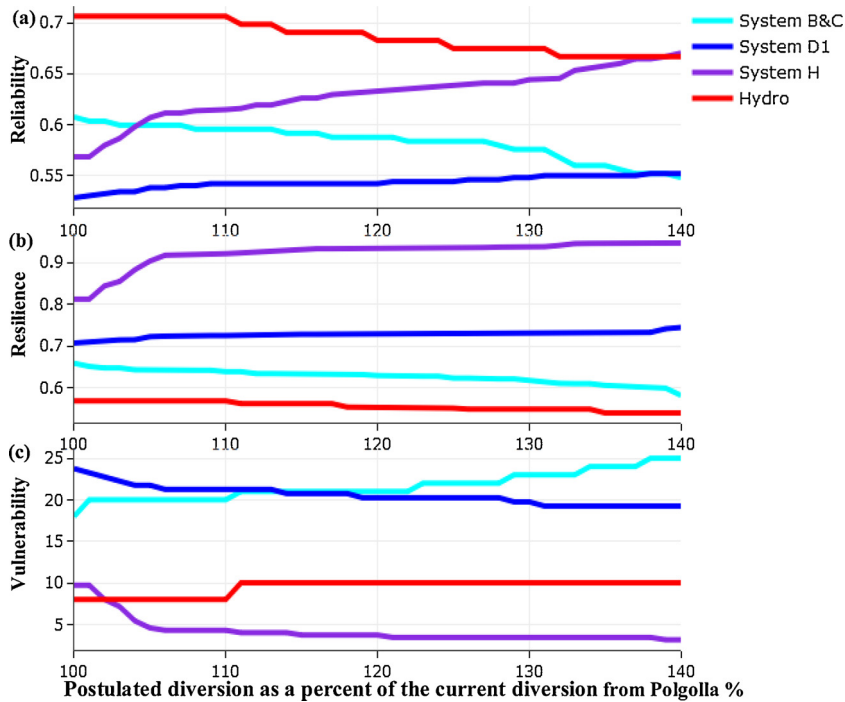


Fig. 11. Performances of agricultural systems and hydropower plants for increasing water diversion to the north from the Polgolla diversion weir.

and H) do not have the capacity to store the additional water and so agricultural production remains flat and spill losses increase. A trade-off frontier curve between hydropower and paddy yield for different increases in diversion shows that the feasible region for decisions about the tradeoff is between an average annual range of 1012–1034 Mtonnes of paddy and 2186–2229 GW h of hydropower generation (Fig. 13(b)).

5. Discussion

Under the present policy for water diversion at Polgolla, the reliability, resilience and vulnerability values show how different issues can affect different systems (Table 2). Hydropower exceeds the recent 15-year average more than 70% of time using hydropower generation of the recent past years (2002–2017) for comparison. However, the low resilience (0.57) and comparatively high vulnerability (8/126) values demonstrate the uncertainty of hydropower generation. Limitations of infrastructure and spatial variability of available water constrain agricultural system performance. For example, system H has a poor reliability value because about 42,000 ha of arable land is supported by only 224 Mm³ of local water storage capacity. However, a large local storage capacity does not improve risk measures if water is not available to supply the reservoirs and tanks. For example, systems B&C (about 48,000 ha) show relatively weak performance despite being supported by a large water storage capacity of 742 Mm³ (Figs. 9 and 11). System D2, which has the best performance measures, is a good example for high local storage capacity and an abundant supply of water. Although D1 is adjacent to D2, its risk measures are much worse due to a lack of infrastructure to distribute water.

One drought adaptation measure is to reduce the amount of cultivated land. Improvement of performances of agriculture systems under this adaptation measure varies across systems. For example, system H shows large improvements in resilience at 80% of land cultivated whereas systems D1, B and C show much more modest improvement (Fig. 9(b)). Due to advantageous climate and soil properties system H has a lower crop water requirement compared to other systems (Fig. 4) and improves at a high rate in terms of resilience as the extent of arable land cultivated decreases. This also is the reason for the marked improvement shown in System H as increased diversion at Polgolla provides additional irrigation water (Fig. 11).

Reducing the extent of irrigated lands involves trade-offs between improving risk performance measures and reducing the yield and hence economic return of agricultural systems (Fig. 10). The trade-offs are not the same for different agricultural systems due to water availability and infrastructure for water storage. Notably, the resilience improvement in system H is approximately double that in system B&C (Fig. 11). Hence, individual system performance can inform water management decisions.

Performance measures downstream of the diversion at Polgolla are sensitive to the water allocation policy (Fig. 11). As expected, performance of irrigation systems to the north is improved for higher diversions at Polgolla. Beyond about a 16% increase in the diversion, however, water spilling from northern local reservoirs is increased (Fig. 12(a)) and overall paddy production decreases because water is taken away from systems on the main stem of the Mahaweli leading to decreased production there, while the additional water diverted north cannot be stored and used efficiently so paddy production there remains flat (Fig. 13). That is, the fractional agricultural utilization (E_f) decreases because spilling increases. In addition, although we have not accounted for

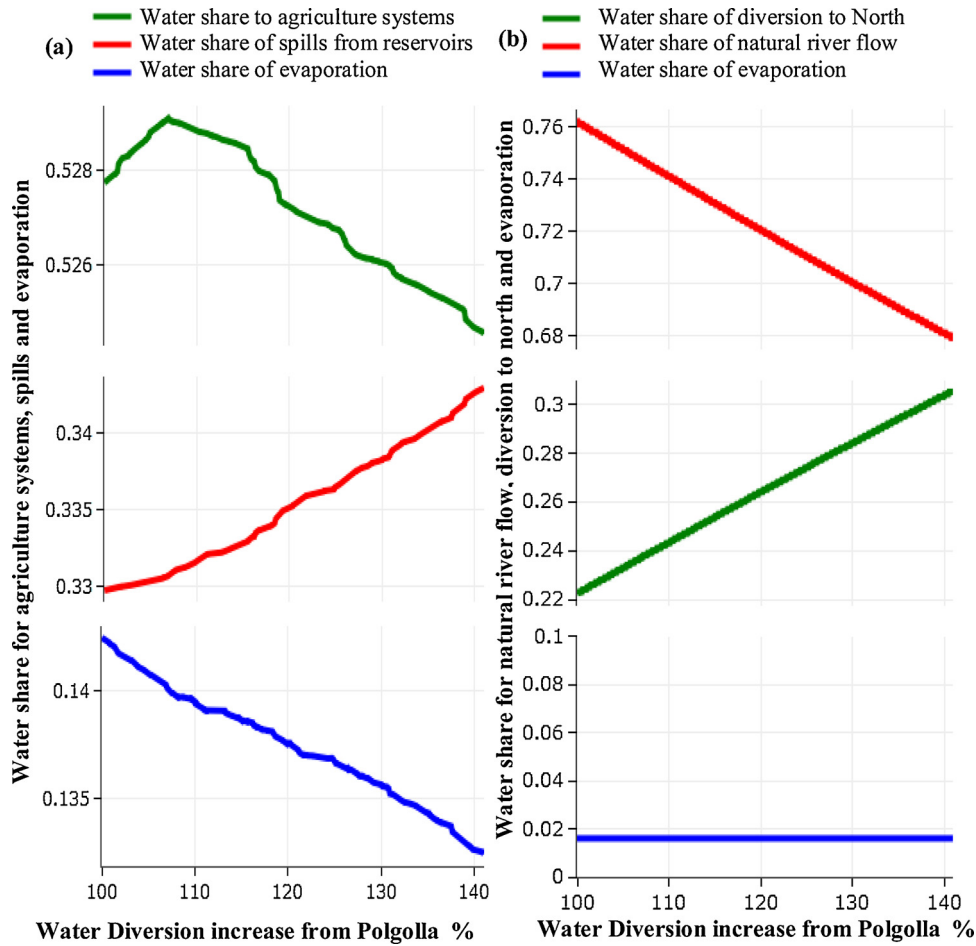


Fig. 12. (a) Water balance among agricultural systems, evaporation loss and spilling from reservoirs (b) Mahaweli river flow and evaporation from downstream reservoirs.

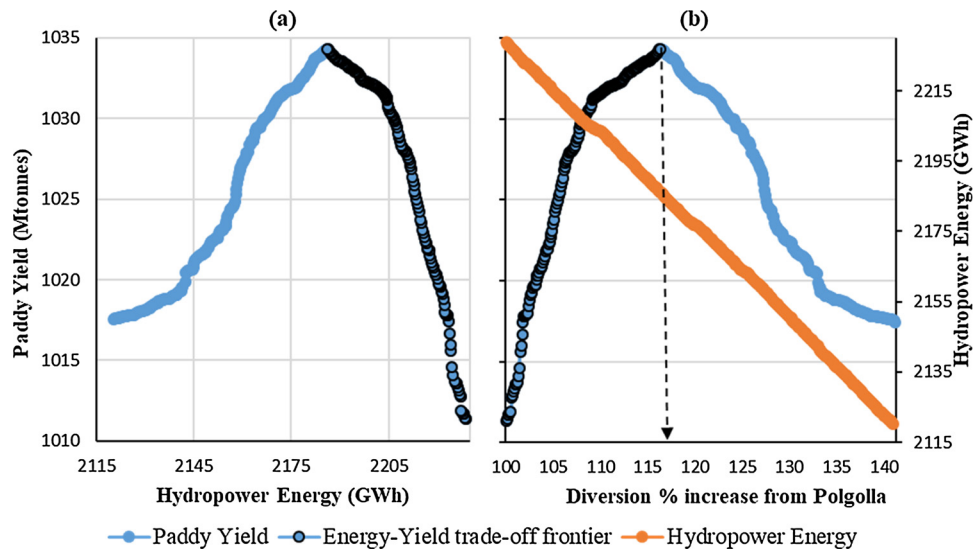


Fig. 13. Agriculture and energy performance according to increasing Polgolla water diversion to the dry northern area (a) Variation of paddy yield (blue) and hydropower generation (orange) (b) Trade-off between paddy yield and hydropower generation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

environmental impacts in our analysis, significant decreases in flow in the main Mahaweli River will negatively impact social and natural capital downstream.

Our results indicate that a simulation model based on a system dynamics approach can provide information to assist in analyzing consequences of water allocation decisions. A relatively simple model such as we propose can be useful for a screening analysis of the impacts of proposed water allocation policies using a modest amount of data about the water resources project. Our case study of the Mahaweli system shows that it is possible to develop a simulation model for a complex reservoir cascade using basic simulation blocks; reservoir, hydropower plant, agriculture system and water distribution decision. The Simulink platform (MathWorks Simulink, 2018) is easy to understand and can be used by those with modest programming skills. Components of the reservoir cascade can be visualized and the model can be modified easily according to new infrastructure additions and parameter changes. The relatively simple simulation model developed in the MATLAB/Simulink platform can be used for studying similar reservoir systems.

The performance of reservoir cascade systems in terms of economic products as well as in risk measures provide information to inform decisions about the operation and planning for future alternatives. Analysis of the performance of components of the overall system indicates limitations imposed by existing infrastructure and also changes that would result from proposed new infrastructure. Overall cascade performance measures in terms of economic products expose the energy-yield trade-offs of water sharing between hydropower and irrigated agriculture. Reliability, resilience and vulnerability indices of agricultural systems vary according to the spatial variability of land properties, water availability, and infrastructure facilities. Knowledge about these variabilities across the systems can be used to fine tune system level decisions about the tradeoffs between increasing yields and increasing RRV metrics. Reducing the extent of cultivated land or changing of water allocations at one location provide only marginal improvement of RRV measures of most of the systems. Because changing the operation policy of one major location can marginally increase agricultural production but substantially decrease hydropower generation, it is critical that a combination of important components in the reservoir cascade be managed concurrently.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest associated in this manuscript.

Acknowledgements

This research is part of a multidisciplinary research initiative called Adaptation to Precipitation Trends in Sri Lanka (ADAPT-SL) at Vanderbilt Institute for Energy and Environment (VIEE). The work is supported by National Science Foundation, United States, WSC Program Grant No. NSF-EAR 1204685. The authors thank Mr. Sunil Liyanagama, Ex-Director, Water management secretariat of Mahaweli Authority of Sri Lanka and the anonymous reviewers for their guidance on this work. All data used in this study are from the Water management secretariat of Mahaweli Authority of Sri Lanka (<http://mahaweli.gov.lk/en/water.html>) and Generation Planning Division of Ceylon Electricity Board (<http://www.ceb.lk/>). Because the model code includes government information about dams and power plants, the total simulation model cannot be made public. Scripts to generate graphs and analysis, and basic simulation blocks of the model can be found at https://github.com/thusharadesilva/Mahaweli_simulation.git. Please contact the authors to obtain other data or model results.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2019.100624>.

References

- Ajami, N.K., Hornberger, G.M., Sunding, D.L., 2008. Sustainable water resource management under hydrological uncertainty. *Water Resour. Res.* 44, 1–10. <https://doi.org/10.1029/2007WR006736>.
- Asefa, T., Wanakule, N., Adams, A., Shelby, J., Clayton, J., 2014. On the use of system performance metrics for assessing the value of incremental water-use permits. *J. Water Resour. Plan. Manag.* 140, 04014012. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000388](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000388).
- Chanda, K., 2014. Reliability-resilience-vulnerability drought index. *Water Resour. Res.* 1–15. <https://doi.org/10.1002/2014WR015703>. Received.
- Digna, R.F., Mohamed, Y.A., van der Zaag, P., Uhlenbrook, S., van der Krogt, W., Corzo, G., 2018. Impact of water resources development on water availability for hydropower production and irrigated agriculture of the Eastern Nile basin. *J. Water Resour. Plan. Manag.* 144, 1–13. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000912](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000912).
- Fowler, H.J., Kilsby, C.G., O'Connell, P.E., 2003. Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resour. Res.* 39. <https://doi.org/10.1029/2002WR001778>.
- Hashimoto, T., Loucks, D.P., Stedinger, J., 1982. Reliability, resilience and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* 18, 14–20. <https://doi.org/10.1029/WR018i001p00014>.
- Huizar, L.H., Lansey, K.E., Arnold, R.G., 2018. Sustainability, robustness, and resilience metrics for water and other infrastructure systems. *Sustain. Resilient Infrastruct.* 3, 16–35. <https://doi.org/10.1080/23789689.2017.1345252>.
- Jahandideh-Tehrani, M., Bozorg Haddad, O., Mariño, M.A., 2014. Power generation simulation of a hydropower reservoir system using system dynamics: case study of karoon reservoir system. *J. Energy Eng.* 140, 04014003. [https://doi.org/10.1061/\(ASCE\)EY.1943-7897.0000179](https://doi.org/10.1061/(ASCE)EY.1943-7897.0000179).
- Jain, S.K., Bhunya, P.K., 2008. Reliability, resilience and vulnerability of a multipurpose storage reservoir. *Hydrol. Sci. J.* 53, 434–447. <https://doi.org/10.1623/hysj.53.2.434>.
- Kling, H., Stanzel, P., Preishuber, M., 2014. Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *J. Hydrol. Reg. Stud.* 1, 17–43. <https://doi.org/10.1016/j.ejrh.2014.05.002>.

- Loucks, D.P., 2005. Examples Decision Support Systems for River Basin Simulation [WWW Document]. eCommons Cornell's Digit. Repos. URL <https://ecommons.cornell.edu/handle/1813/2830> (accessed 6.1.18).
- Loucks, D.P., van Beek, E., 2017. Water resource systems planning and management; An Introduction to methods, models, and applications. Springer International Publishing, Cham. <https://doi.org/10.1007/978-3-319-44234-1>.
- Mahaweli Authority of Sri Lanka, 2017. Seasonal Summary Reports (2002-2017).
- Mateus, M.C., Tullios, D., 2016. Reliability, sensitivity, and vulnerability of reservoir operations under climate change. *J. Water Resour. Plan. Manag.* 143, 04016085. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000742](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000742).
- MathWorks Simulink, 2018. Simulations and Model Based Design [WWW Document]. URL <https://www.mathworks.com/products/simulink.html> (accessed 1.30.18).
- Mondal, M.S., Wasimi, S.A., 2007. Evaluation of risk-related performance in water management for the Ganges Delta of Bangladesh. *J. Water Resour. Plan. Manag.* 133, 179–187. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2007\)133:2\(179\)](https://doi.org/10.1061/(ASCE)0733-9496(2007)133:2(179)).
- Moy, W.-S., Cohon, J.L., ReVelle, C.S., 1986. A programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir. *Water Resour. Res.* 22, 489–498. <https://doi.org/10.1029/WR022i004p00489>.
- Räsänen, T.A., Joffe, O.M., Someth, P., Thanh, C.T., Keskinen, M., Kumm, M., 2015. Model-based assessment of water, food, and energy trade-offs in a cascade of multipurpose reservoirs: case study of the sesan tributary of the Mekong River. *J. Water Resour. Plan. Manag.* 141, 05014007. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000459](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000459).
- Rivera, A., Gunda, T., Hornberger, G.M., 2018. Minimizing irrigation water demand: an evaluation of shifting planting dates in Sri Lanka. *Ambio* 47, 466–476. <https://doi.org/10.1007/s13280-017-0993-8>.
- Saha, S., Roy, D., Mazumdar, A., 2017. Performance of a system of reservoirs on futuristic front. *Appl. Water Sci.* 7, 2667–2680. <https://doi.org/10.1007/s13201-016-0484-2>.
- Sakthivadivel, R., Molden, D., 1999. Water accounting to assess use and productivity of water. *Int. J. Water Resour. Dev.* 15 (1-2), 55–71. <https://doi.org/10.1080/07900629948934>.
- Sandoval-solis, S., Mckinney, D.C., Loucks, D.P., 2011. The extent of the market and the optimal degree of specialization *. *J. Water Resour. Plan. Manag.* 7, 381–390. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000134](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000134).
- Sharifi, A., Kalin, L., Tajrishy, M., 2013. System dynamics approach for hydropower generation assessment in developing watersheds: case study of Karkheh River Basin. *Iran. J. Hydrol. Eng.* 18, 1007–1017. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000711](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000711).
- Simonovic, S.P., Arunkumar, R., 2016. Comparison of static and dynamic resilience for a multipurpose reservoir operation. *Water Resour. Res.* 52, 8630–8649. <https://doi.org/10.1002/2016WR019551>.
- Srdjevic, Z., Srdjevic, B., 2017. An extension of the sustainability index definition in water resources planning and management. *Water Resour. Manag.* 31, 1695–1712. <https://doi.org/10.1007/s11269-017-1609-6>.
- Tilmant, A., Goor, Q., Pinte, D., 2009. Agricultural-to-hydropower water transfers: sharing water and benefits in hydropower-irrigation systems. *Hydrol. Earth Syst. Sci. Discuss.* 13, 1091–1101. <https://doi.org/10.5194/hess-13-1091-2009>.
- Tinoco, V., Willems, P., Wyseure, G., Cisneros, F., 2016. Evaluation of reservoir operation strategies for irrigation in the Macul Basin. Ecuador. *J. Hydrol. Reg. Stud.* 5, 213–225. <https://doi.org/10.1016/j.ejrh.2015.12.063>.
- US Army Corps of Engineers, 2013. HEC-ResSim Reservoir System Simulation User's Manual Computer Program Documentation: Version 3.1.
- Vieira, E., de, O., Sandoval-Solis, S., 2018. Water resources sustainability index for a water-stressed basin in Brazil. *J. Hydrol. Reg. Stud.* 19, 97–109. <https://doi.org/10.1016/j.ejrh.2018.08.003>.
- Zhang, C., Xu, B., Li, Y., Fu, G., 2017. Exploring the relationships among reliability, resilience, and vulnerability of water supply using many-objective analysis. *J. Water Resour. Plan. Manag.* 143, 04017044. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000787](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000787).