J. Earth Syst. Sci. (2019)128 229
https://doi.org/10.1007/s12040-019-1258-7

A box-model approach for reservoir operation during extreme rainfall events: A case study

P Anandharuban[1], Michele La Rocca[2] and L Elango[1,*]

[1]*Department of Geology, Anna University, Chennai 600 025, India.*
[2]*Department of Engineering, Roma Tre University, Via Vito Volterra 62, 00146, Rome, Italy.*
**Corresponding author. e-mail: elango34@hotmail.com*

MS received 17 April 2019; revised 13 June 2019; accepted 17 June 2019

Extreme rainfall events in an urban area pose various challenges to the water resource managers in terms of flood mitigation, inundation, water conservation and harvesting for drinking water supply. The objective of this study is to apply the box-model approach to evaluate reservoir operation during extreme rainfall events. A large water supply reservoir in Chennai was chosen to carry out this study. A box model, based on input–output parameters, is proposed to simulate the reservoir operation and hydraulic behaviour. Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) has been used to simulate the reservoir inflow hydrograph and to understand the run-off characteristics of the basin. Three extreme rainfall events occurred in past have been selected for the analysis. Three different scenarios have been framed to assess the reservoir performance. Reducing the initial storage to 50% and releasing water at the beginning of the event gives a possible solution for flood mitigation in reducing the outflow volume by 9–37% and delaying the time to peak by 1–6 h. Though the reduced outflow volume from this reservoir is less, it can help to mitigate the flood inundation to a significant extent. Thus the box-model approach presented here can be utilised as a simple tool to generate the various combinations of outflow hydrographs for any reservoir.

Keywords. Reservoir operation; box model; flood; HEC-HMS; water scarcity.

1. Introduction

Due to rapid urbanisation, population growth and increased agricultural activities, the demand for water is increasing, especially in developing countries. Climate change, unsustainable consumption practices and poor management practices pose as a challenge to the water supply and it is becoming very difficult to meet the demands (Raje and Mujumdar 2010). Frequent floods and droughts are some of the consequences of climate change, which in turn have been resulting in socio-economic hardships throughout the globe. Since 1992, about 4.2 billion people have been affected by floods, droughts and storms, causing damage of about US$1.3 trillion worldwide (Velasquez 2012). In such circumstances, single and multi-purpose reservoirs play a vital role in flood control and flood water utilisation for meeting the future water demand (Liu *et al.* 2015).

Priorities and operation rules are set considering the purpose of the reservoir. Although reservoirs are constructed for specific requirements, during extreme rainfall it could not be possible to adhere to the operational rules as the priorities may change. For example, water supply reservoir may

Published online: 20 August 2019

need to release the water to prevent flooding during extreme rainfall events. Hence extreme rainfall events stand as a major challenge for reservoir managers since they have to decide the amount of water to be released from the reservoir. Reservoir operation needs to be done by considering the safety of the reservoir and downstream region as well as the future water need (Huang and Hsieh 2010). However, the flood inundation downstream and future water supply shortages are associated with reservoir operation rules particularly in the upper reservoir level limits (Chang *et al.* 2017). Timely decision on the release of water from the reservoir will influence the short-term and long-term planning of flood control during storms, water supply distribution and reservoir operation rule optimisation (Cheng *et al.* 2017). Hence, this decision demands regular restructuring of its guidelines, notes and parameters based on the recent flood events so as to present new scenarios according to demands (Ahbari *et al.* 2019).

In this context, research on reservoir operation, routing, flood control, water supply and optimisation of reservoir have been studied with different tools and algorithms for various reservoirs (Huang and Hsieh 2010; Raje and Mujumdar 2010; Hsu *et al.* 2015; Chang *et al.* 2017; Ahbari *et al.* 2019). Uysal *et al.* (2018) applied optimisation technique for reservoir operation to account for the short-term and long-term goals with predictive control techniques. Cheng *et al.* (2017) studied the flood control and water supply shortages with integrated approach using optimisation model and Monte Carlo simulations in Da-Ha creek basin in Taiwan. Saadatpour *et al.* (2017) have applied various operation strategies to enhance optimisation by reducing spatial resolution of CE-QUAL-W2 software package and integrate it with artificial neural network for meeting water demands and hydropower generation. Coerver *et al.* (2018) analysed the possibilities of integrating the reservoir operating rules with the global hydrologic models for the inflow and release predictions. They have used fuzzy logic and adaptive network based fuzzy inference system for simulation algorithm to simulate the inflow and release in 11 reservoirs in central Asia, the Unite States and Vietnam. Ahmad *et al.* (2014) have discussed the research on reservoir optimisation techniques using evolutionary computational algorithms such as artificial bee colony and gravitational search optimisation and their application for problems like flood control, hydroelectric power management, water supply, water allocation, operation rule optimisation. These studies have been done with the help of algorithms and tools which require large data sets. The interpretation of the weights in neural network concepts is difficult and it is a time-consuming process. To overcome these downsides, a simple box-model approach is proposed in this study. Box-model approaches have been used mainly to model the water and salinity transport in lake systems (Sakov and Parslow 2004; Rouwet and Tassi 2011; Li *et al.* 2015). These studies have used the box model only for the calculation of water balance. In this study we present this box-model approach for operation of a reservoir under extreme rainfall condition. This box model ignores the details and depends only on input–output quantities. Such an approach has not been carried out yet for the extreme rainfall conditions and reservoir operations. Hence, the objective of this study is to apply the box-model approach to evaluate reservoir operation during extreme rainfall events. The Chembarambakkam reservoir which is located in west of Chennai city, India, has been chosen to test the approach developed here.

2. Materials and methods

2.1 *Study area*

Chennai is one of the important metropolitan cities of India, known as the ‘Gateway of south India’. With rapid urbanisation, urban population of this city had the growth rate of 7.8% during 2001–2011 and current population of the urban agglomeration is more than 8 million. The topography of this area is low lying, flat with gentle slope and elevation ranging from 1.32 to 161.63 m above mean sea level. This area has a semi-arid tropical climate with high humidity, mean annual temperature of 30°C. The average rainfall of this city is 1350 mm, however majority of rainfall is received during October–December and average annual number of rainy days is only 59 (IMD, Chennai). Frequent floods and droughts in the city are common in recent time due to extremity of rainfall occurrence. Per capita availability of water supply is 40–100 l/day which is the lowest among the megacities of India (Srinivasan *et al.* 2010). Chembarambakkam, Poondi, Puzhal and Cholavaram reservoirs supply water to Chennai. The Chembarambakkam reservoir has the highest total storage capacity of 103.21 Mm^3 and it gets filled once in 3 yr during the monsoon. It is located in the western part of the Chennai metropolitan city and the surplus water of Chembarambakkam reservoir forms one of the two major tributaries to Adyar River (figure 1). Figure 2 represents the schematic of the Chembarambakkam reservoir, with elevation and respective storage capacity. Since the Chembarambakkam reservoir is a large water storage structure, the operation of this reservoir has major impact on flood inundation in the downstream region. In the absence of dependable flood forecasting arrangements, wrong discretion and decision making in advance releases both in time and in quantity may result in a higher flood peak in the Adyar down below.

2.2 *Methodology*

A box model is developed for the analysis of the Chembarambakkam reservoir and its operation. The dynamics of the Chembarambakkam reservoir has been analysed using the box model for the extreme rainfall events of 2005, 2008 and 2015. 2005 event was 2 days long with a total rainfall of 236 mm, 2008 event was 5 days long with 255 mm and 2015 event was about 2 days with 474 mm. During the selected extreme events, i.e., 2005, 2008 and 2015, the calamity happened during the second highest storm of the monsoon season. It gives an additional challenge for the reservoir operation in terms of flood mitigation due to its wet antecedent moisture condition (AMC). Hence, these three events were selected for analysis and the complete methodology followed in this work is depicted in figure 3.

2.2.1 *Rainfall run-off process*

Remote sensing based HEC-GeoHMS tool was used for translating GIS spatial information into model input files for Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS; Feldman 2000; Doan 2003). Shuttle Radar Topography

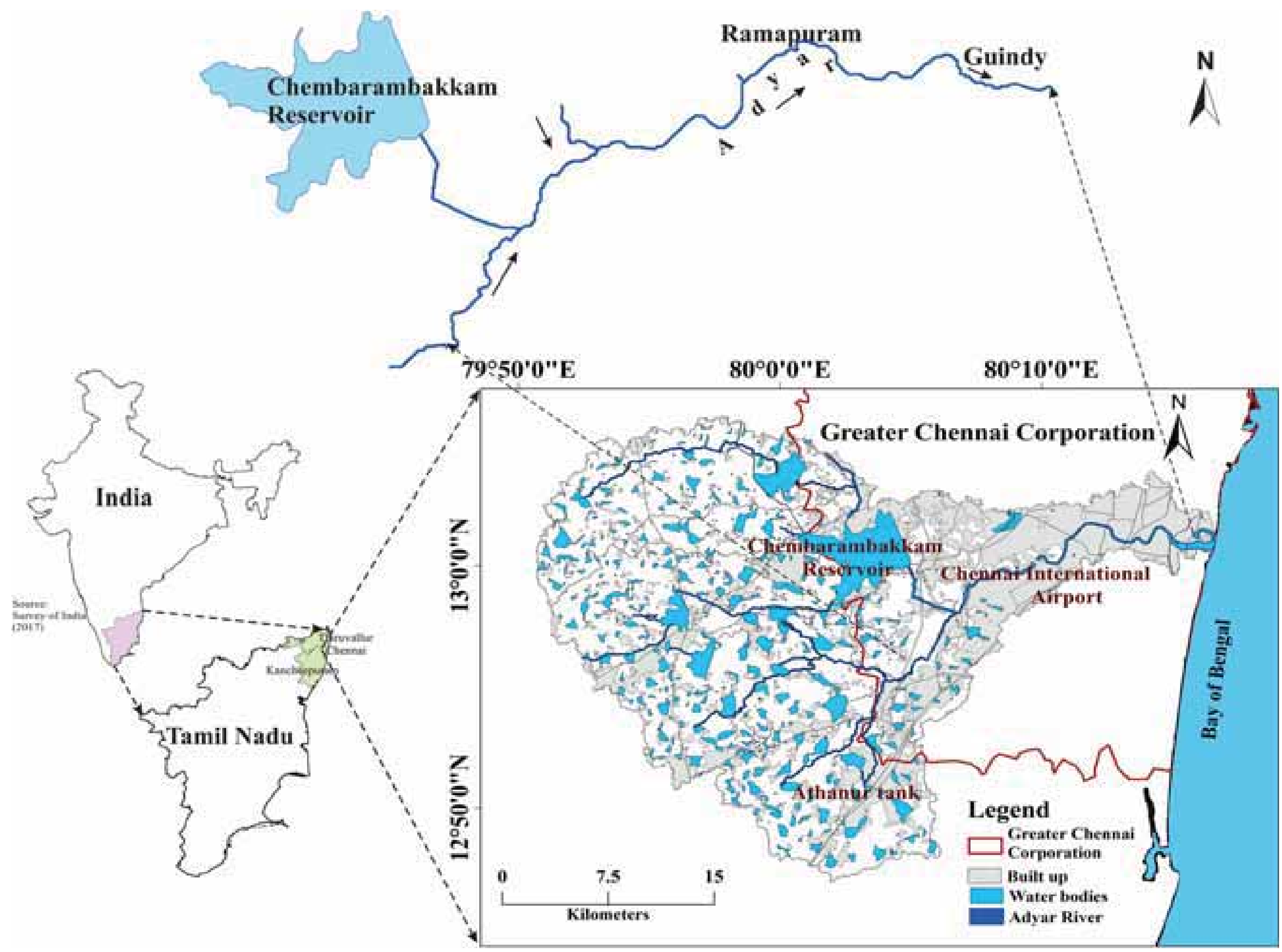

Figure 1. Study area.

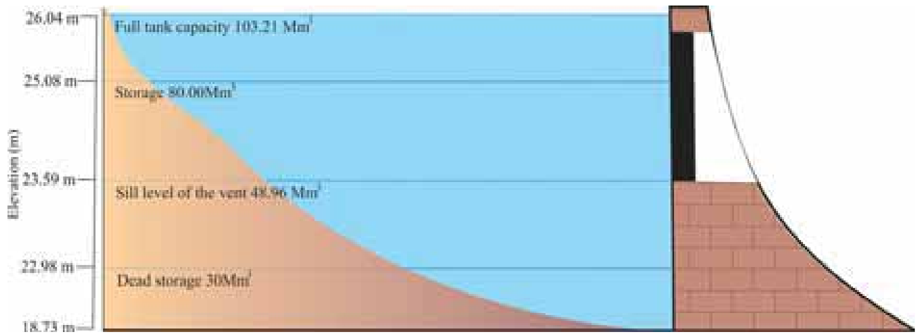

Figure 2. Schematic of Chembarambakkam reservoir.

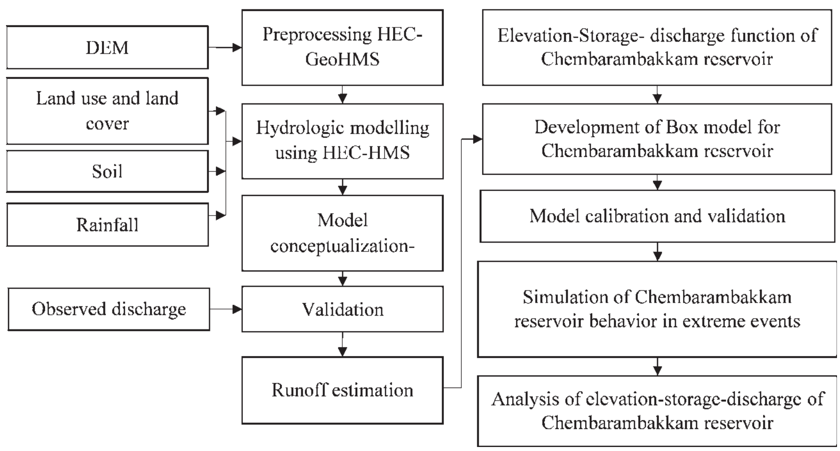

Figure 3. Methodology of the reservoir dynamics.

Mission (SRTM) digital elevation model (DEM) of 30 m × 30 m resolution was used to derive physical properties of the basin and the river. Figure 4 represents the basin model set up in HEC-HMS. Event, lumped, empirical and fitted parameter models were chosen for basin conceptualisation which includes run-off volume models, direct run-off models and routing models. Land use and land cover, hydrologic soil group and rainfall information are required to simulate the run-off processes in HEC-HMS. Soil conservation service (SCS) method was used to model run-off volume and direct run-off, which needs weighted curve number (CN) that are derived from the soil group and land use and land cover data. SCS equations modified to suit the Indian condition as given by Kumar *et al.* (1991) were applied in this study (table 1). From which curve number for AMC III were estimated for the events using equation (1):

$$CN_3 = CN_2 \times \exp(0.00673 \times (100 - CN_2)), \quad (1)$$

CN_3 is the curve number for AMC III and CN_2 is the curve number for AMC II.

Land use land cover map prepared from the LISS-III image available at the Institute of Remote Sensing, Anna University, Chennai, India, for November 2008 and October 2015 was used. The changes in land use and land cover have been accounted based on the curve number. Soil data was collected from National Bureau of Soil Survey and Land Use Planning, India. The Muskingum routing method was used for the water movement in the reach.

Atmospheric conditions of the basin are given as input in meteorological model of HEC-HMS. Specified hyetograph method was applied for the selected events. Gauge weight method was used to account the spatial variation in the rainfall over the basin. Thiessen polygon method was applied to calculate the weights for each rain gauges (figure 5). Control specifications are given to simulate the flood hydrograph and rainfall flood volume for the events. Chembarambakkam reservoir was simulated with the storage-discharge function and elevation-storage function in the model. Outflow was regulated with the outflow curve method.

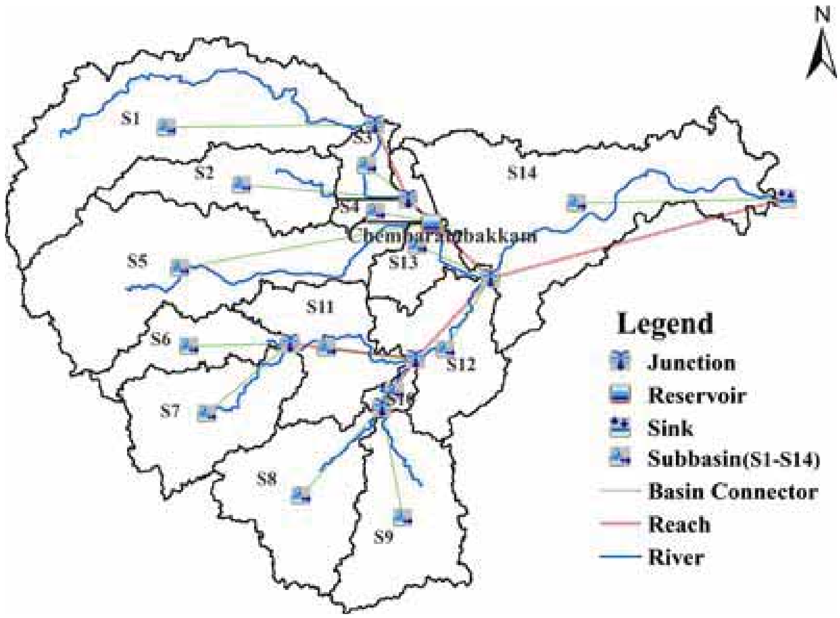

Figure 4. HMS model set-up.

Table 1. *Run-off curve numbers for (AMC II) Indian conditions (Kumar et al. 1991).*

Sl. no.	Land use/land cover	Hydrologic conditions	Run-off curve numbers for hydrologic soil group A	B	C	D
1	Cultivated land	Poor	68	76	82	84
		Good	62	72	78	82
		Paddy	95	95	95	95
2	Forest	Dense	26	40	58	61
		Open	28	44	60	64
3	Fallow (includes bare ground)		68	79	86	89
4	Waste land		71	80	85	98
5	Impervious surface		77	86	91	93
6	Water bodies		100	100	100	100

Initial conditions for every event were given as input based on the storage. Selected events were simulated by combining basin model, meteorological model and control specifications. Accordingly flood hydrograph and flood volumes were calculated.

2.2.2 *Simulation of flow in the box model*

A box model was proposed as a tool for the simulation of the dynamics of this reservoir when subjected to extreme rainfall. The box model considers the reservoir as a 'black box', whose evolution is determined by input–output parameters. Figure 6 presents the storage-elevation-discharge function of the reservoir operation (PWD, Tamil Nadu) which was used to define the box model.

The equation of the water balance can be written as

$$\frac{\mathrm{d}V}{\mathrm{d}t} = Q_{\mathrm{in}} - Q_{\mathrm{out}} + Q_{\mathrm{rain}} - Q_{\mathrm{ev}}, \qquad (2)$$

where V, Q_{in}, Q_{rain}, Q_{out} and Q_{ev} are, respectively, the volume of water contained in the reservoir at time t, the inflow, the flow entering the reservoir due to rainfalls, the outflow and the evaporating flow of water.

The volume of water is given by

$$V = \int_0^h A(z)\mathrm{d}z. \qquad (3)$$

With $A = A(z)$, the surface of the reservoir at height z from the bottom and h, the depth of the

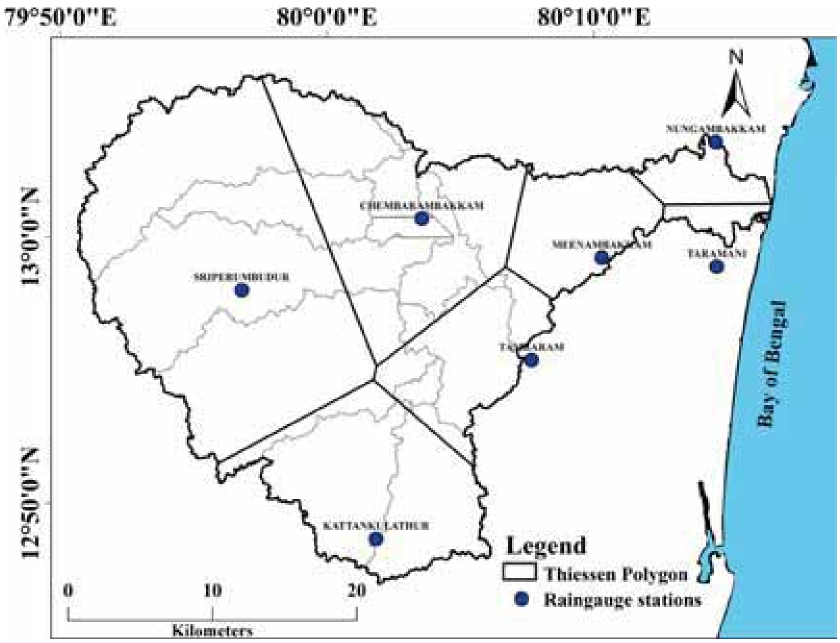

Figure 5. Rain gauge locations and its spatial influence.

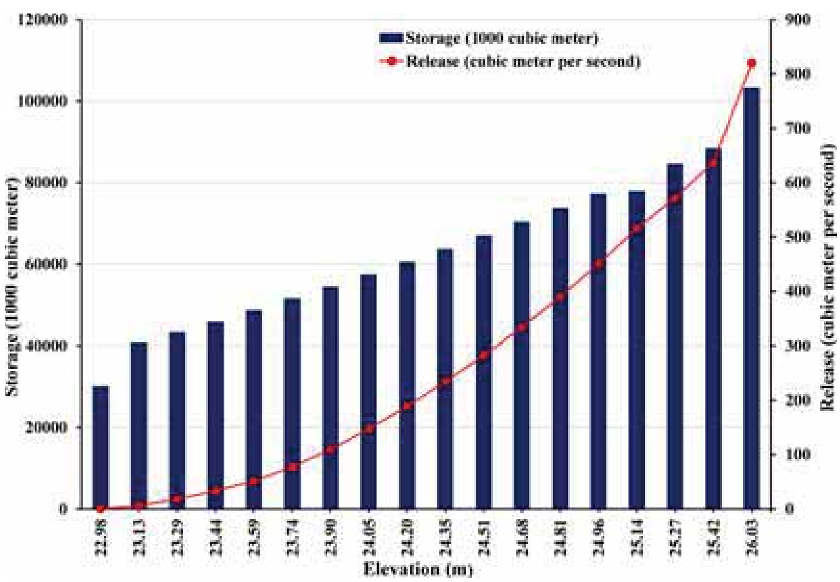

Figure 6. Elevation-storage-discharge function of Chembarambakkam reservoir.

reservoir from the bottom, the left-hand side of equation (2) can be expressed as

$$\frac{\mathrm{d}V}{\mathrm{d}t} = A(h)\frac{\mathrm{d}h}{\mathrm{d}t}. \tag{4}$$

The function $A = A(h)$ is a monotonic increasing function, whose graph is plotted in figure 7.

The inflow Q_{in} is a given function of time, while the outflow Q_{out} is given as the sum of the discharges outflowing from the total number of N_{sl} sluice gates:

$$Q_{\mathrm{out}} = C_{\mathrm{d}}\sqrt{2g}\sum_{i=1}^{N_{\mathrm{sl}}} b_i\left(h - h_i^{\mathrm{sl}}\right)^{3/2}, \tag{5}$$

where b_i and h_i^{sl} are the width and the opening of the ith sluice gate, respectively. Equation (5) is obtained imposing that the flow on the sluice gate becomes critical (figure 8). C_{d} is a discharge coefficient ($C_{\mathrm{d}} \approx 0.4$). Equation (5) gives a vanishing discharge if $h \leq h_i^{\mathrm{sl}}$.

The flow entering the reservoir due to rainfall is estimated by

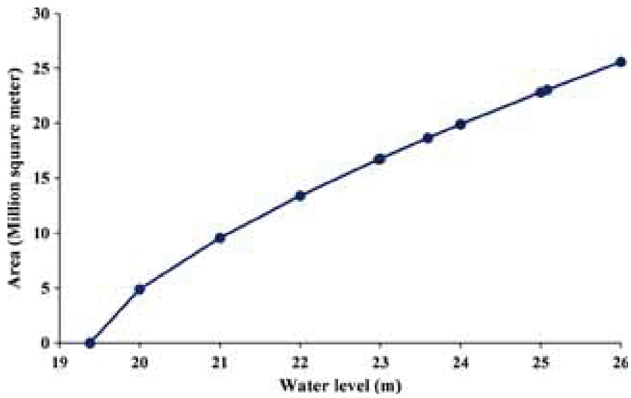

Figure 7. Surface area of the reservoir versus water level.

$$Q_{\text{rain}} = A(h)\frac{0.001p}{T}. \tag{6}$$

Here p, the rainfall on the reservoir, is expressed in millimetres per day and $T = 86{,}400$ s. Finally Q_{ev} is estimated by the formula proposed by Visentini (1937):

$$Q_{\text{ev}} = B\theta^{1.5}, \tag{7}$$

where θ is the monthly average temperature expressed in °C and B is an empirical coefficient. The constant B was estimated and validated based on the daily water-level data of the Chembarambakkam reservoir and it is 2. Q_{ev} is expressed in millimetres per month.

Equation (2) is solved by means of a standard fourth-order Runge–Kutta solver, together with equations (4–7).

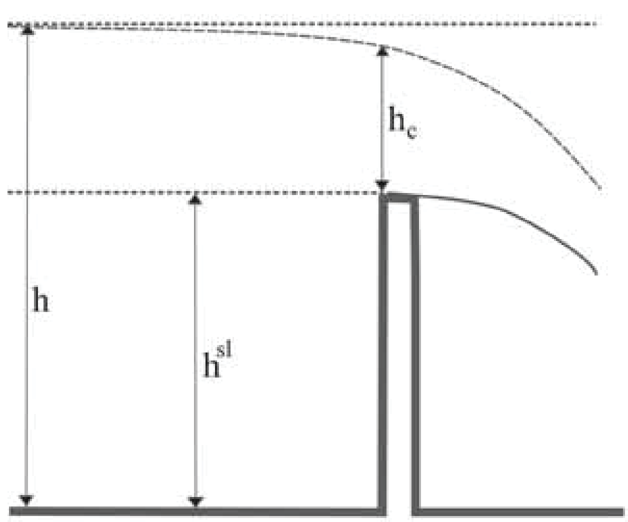

Figure 8. Sketch of the sluice gate (the flow is critical just over the crest).

3. Results and discussions

3.1 *Run-off characteristic of the basin and inflow to the Chembarambakkam reservoir*

As the Adyar river basin does not have continuous flow measurements, the only measured extreme flood event was in 2008. Hence the model was validated with respect to the 2008 flood event measured at the outlet of the basin (figure 9a). It is observed that the simulated and observed peak flow is comparable, whereas there is some difference in the peak of the observed and simulated flow (figure 9b). This is because of the unaccounted surface run-off that would have joined the river downstream the Chembarambakkam reservoir and rainfall variation.

Run-off values from different parts of the Adyar basin were studied with respect to the events simulated in the HEC-HMS. The study area is divided into three parts as depicted in figure 10. Area (A) is the upstream part of the Chembarambakkam reservoir which is about 335 km^2; area (B) is the second wing of the Adyar river which is about 352 km^2 and the Adyar river reach in Chennai city is about 140 km^2. The total surface storage capacity of the basin is 189.917 Mm^3; due to the presence of the Chembarambakkam reservoir, the surface storage of the area (A) is 138.285 Mm^3 and area (B) has a surface storage of 48.207 Mm^3. Although this basin has large storage opportunities due to the wet AMC, the cumulative flow from areas (A) and (B) and the city had led to inundation downstream the Adyar river. The total run-off volume generated in the 2008 event is about 184.4965 Mm^3. The run-off contribution from area (A) is 25.80%, area (B) is 53.38% and from Chennai city reach is 20.82%. The total run-off generated in area (A) is less than that from area (B) in all the events (figure 10).

For the 2005, 2008 and 2015 flood events, inflow data to the Chembarambakkam reservoir were taken from the simulated hydrologic modelling. For these events, the peak discharge at the inlet of the Chembarambakkam reservoir was compared and verified with the daily measurement at the inlet (figure 11). Furthermore, these inflow hydrographs were used to simulate the performance of the Chembarambakkam reservoir in the box model. The time to peak, duration of the storm and volume of inflow are completely different in all three events and these variations will help in understanding the function of the reservoir well.

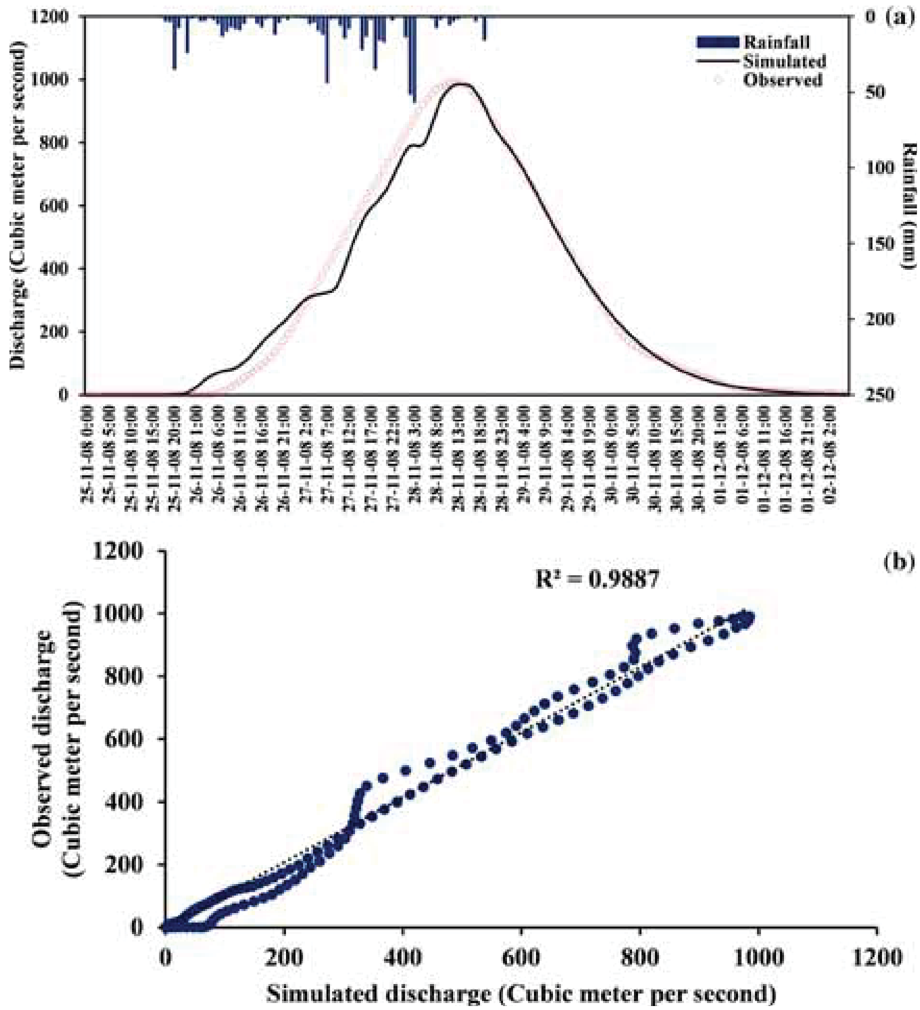

Figure 9. (**a**) Validation of the 2008 event at the outlet of the basin and (**b**) performance of the 2008 event simulation.

3.2 *Simulation of the Chembarambakkam flow*

As this reservoir is for domestic water supply, the daily demand is accounted with the help of the daily monitored water level and the water balance given in equation (2) is validated with respect to the inflow from the basin and the rainfall. During high rainfall events, the sluice gates are operated such that 0.6 m of the top storage may be released in advance, which accounts for 17.27 Mm^3. This operation of gates in the reservoir is included in the box model with equation (5) using the number of vents (N_{sl}) that can be operated and to a height (h^{sl}) up to which the gates can be lifted up and the outflow at various time steps are validated. Simulating the peak outflow using daily time step is a challenge due to the daily changes in evaporation volume (Q_{ev}) and it is achieved to an adequate level of accuracy using equation (7). To replicate the actual reservoir operation, the box model was used to simulate the daily and hourly outflow from the reservoir. The response of the box model is tested with different inflow years from 2003 to 2017. Figure 12 depicts the average monthly rainfall, average storage in the beginning of every month [during normal annual rain year (i.e., 2006), flood years (viz., 2005, 2008 and 2015) and drought years (viz., 2004 and 2016)] and mean monthly storage values from 2003 to 2017. As the Chembarambakkam reservoir supplies 500 million l/day for the domestic water supply requirement of Chennai metropolitan city, the inflow received normally during rainy seasons could be continuously supplied to the city for the entire year and go dry the next year if there is either inadequate or no rainfall. 2015 (December 2015) was a massive flood year, but the storage went almost dry at the end of 2016 (December 2016). In contrast, 2004 was a severe drought year whereas 2005 was a flood year. The storage in the reservoir and the rainfall in the area portray inflow to the reservoir during October to December as being predominant. The storage is

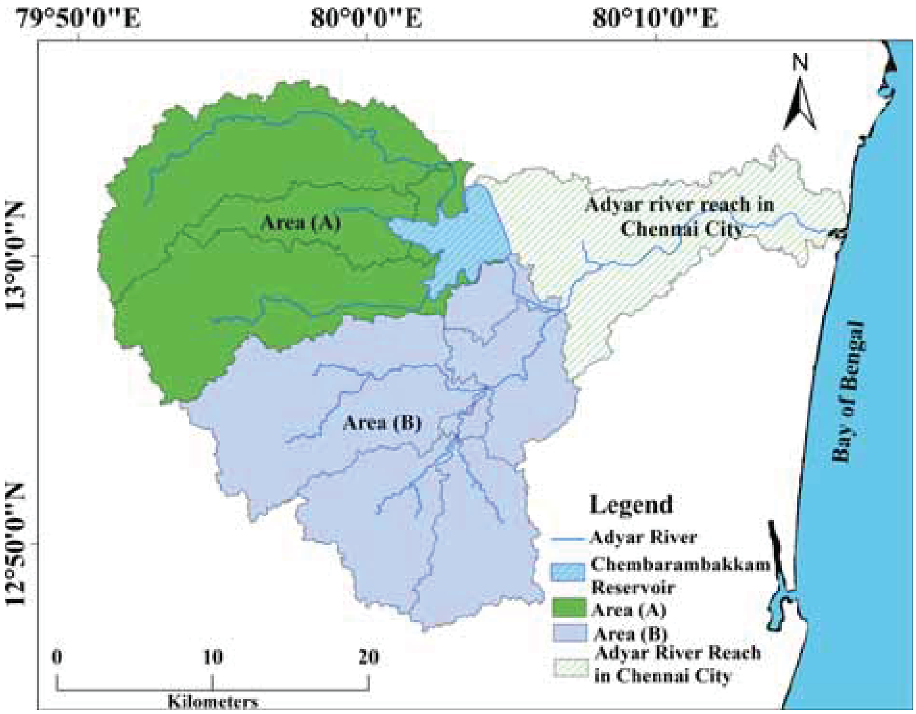

Figure 10. Run-off characteristics of Adyar basin.

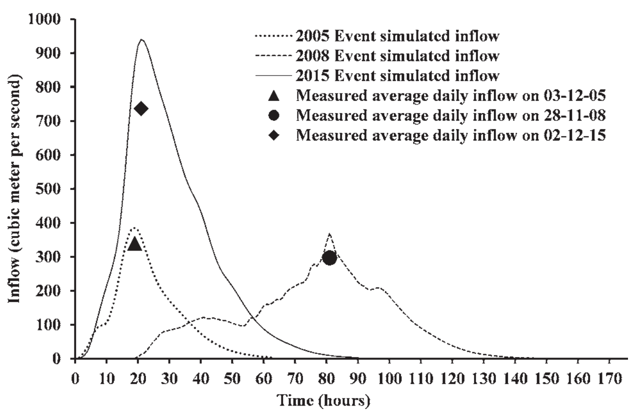

Figure 11. Inflow to Chembarambakkam during 2005, 2008 and 2015.

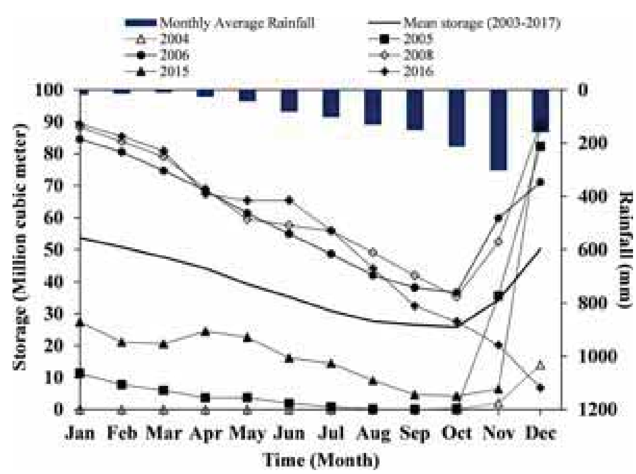

Figure 12. Average storage of Chembarambakkam reservoir.

released only during the extreme events, hence the selected events were chosen for the analysis.

Figure 13(a–c) depicts the inflow and corresponding measured and simulated outflow from the Chembarambakkam reservoir during 2005, 2008 and 2015, respectively at a daily time step. The level of accuracy of the equations involved in the box model, for simulations of reservoir operations are ascertained in terms of the correlation coefficient and Nash–Sutcliffe efficiency and are given in table 2. Based on the performance of the daily flow simulation shows, this box model can be used to simulate different flow conditions.

3.2.1 *Simulation of extreme flow events*

The box model was used to simulate the selected extreme events that occurred in the past. Operation of the reservoir gates is considered and controlled by equation (5) in the box model with respect to the water level and storage. The box model simulates the outflow hydrograph depending upon the initial conditions and the inflow hydrograph (using equation 2). In actual case, the amount of water that flowed into the reservoir was made to flow out during selected extreme events.

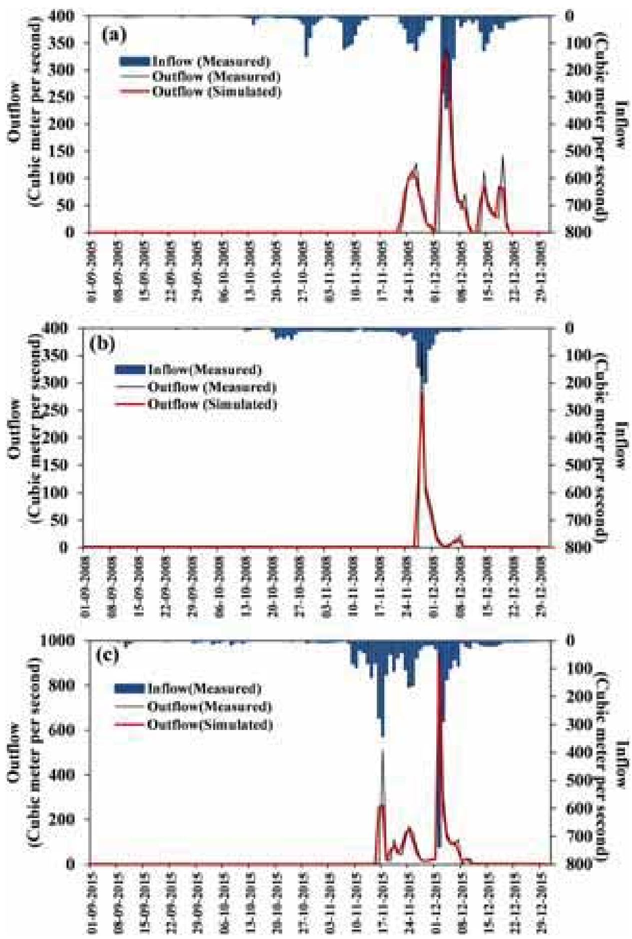

Figure 13. Comparison of simulated outflow in the box model with measured for (**a**) 2005, (**b**) 2008 and (**c**) 2015.

Table 2. *Overall performance of the box model during the daily simulation.*

	Coefficient of correlation		Nash–Sutcliffe	
Year	Water level	Outflow	Water level	Outflow
2004	0.8325	0.7125	0.9485	0.8785
2005	0.8327	0.8786	0.6523	0.8076
2006	0.8742	0.6853	0.8304	0.6554
2007	0.9124	0.7554	0.6724	0.7869
2008	0.8971	0.7649	0.8646	0.7524
2009	0.9479	0.7771	0.4360	0.5806
2010	0.8229	0.5807	0.7462	0.7956
2011	0.7023	0.7957	0.5671	0.9693
2012	0.9078	0.9697	0.6471	0.9467
2013	0.669	0.9469	0.7304	0.7950
2014	0.7542	0.8062	0.9488	0.8901
2015	0.9562	0.6686	0.5963	0.8589
2016	0.8589	0.8628	0.9254	0.9034
2017	0.992	0.9049	0.9485	0.8785

As the actual operation has led to flood inundation downstream the Chembarambakkam reservoir, the box model was used to simulate and verify the possibilities to reduce the outflow from the reservoir and to delay the time to peak for the event. Initial storage in the reservoir at the beginning of the event and outflow from the reservoir during the event has a vital role in the downstream inundation. Hence these factors are used to frame three different scenarios to assess the performance of this reservoir. The initial storage has been set to actual storage that existed during the events in Scenario 1 (i.e., S1) and reduced up to nearly 75–50% in Scenarios 2 and 3 (i.e., S2 and S3), respectively (table 3). The outflow at the beginning of the events is assumed to be higher to delay the time to peak downstream this reservoir. The release rate was decided based on the water level, storage, inflow to the reservoir and the hydraulic ability of the gates in the reservoir. Figure 14 shows the correlation coefficient of simulated events in the box model during the extreme flood events and the performance of the box model is acclaimed.

3.2.2 *Solutions for flood inundation*

Outflow hydrographs were simulated and the volume of water that can be released from the reservoir was estimated for three scenarios for selected events using the box model. For the 2005 event, outflow volume was reduced and the instant of time to peak was increased from the actual case of inflow in Scenarios 1 and 3 (i.e., S1 and S3) (figure 15a, table 4). Two per cent of outflow volume was reduced and time to peak for outflow was delayed

Table 3. *Initial conditions for scenarios analysis.*

		Year		
Sl. no.	Event	2005	2008	2015
	Scenario one			
1	Initial water level (m)	25.19	24.40	25.42
2	Initial storage (Mm^3)	82.375	64.645	88.360
	Scenario two			
3	Initial water level (m)	25.02	24.17	25.02
4	Initial storage (Mm^3)	78.720	59.855	78.720
	Scenario three			
5	Initial water level (m)	24.17	23.88	24.17
6	Initial storage (Mm^3)	59.855	54.360	59.855

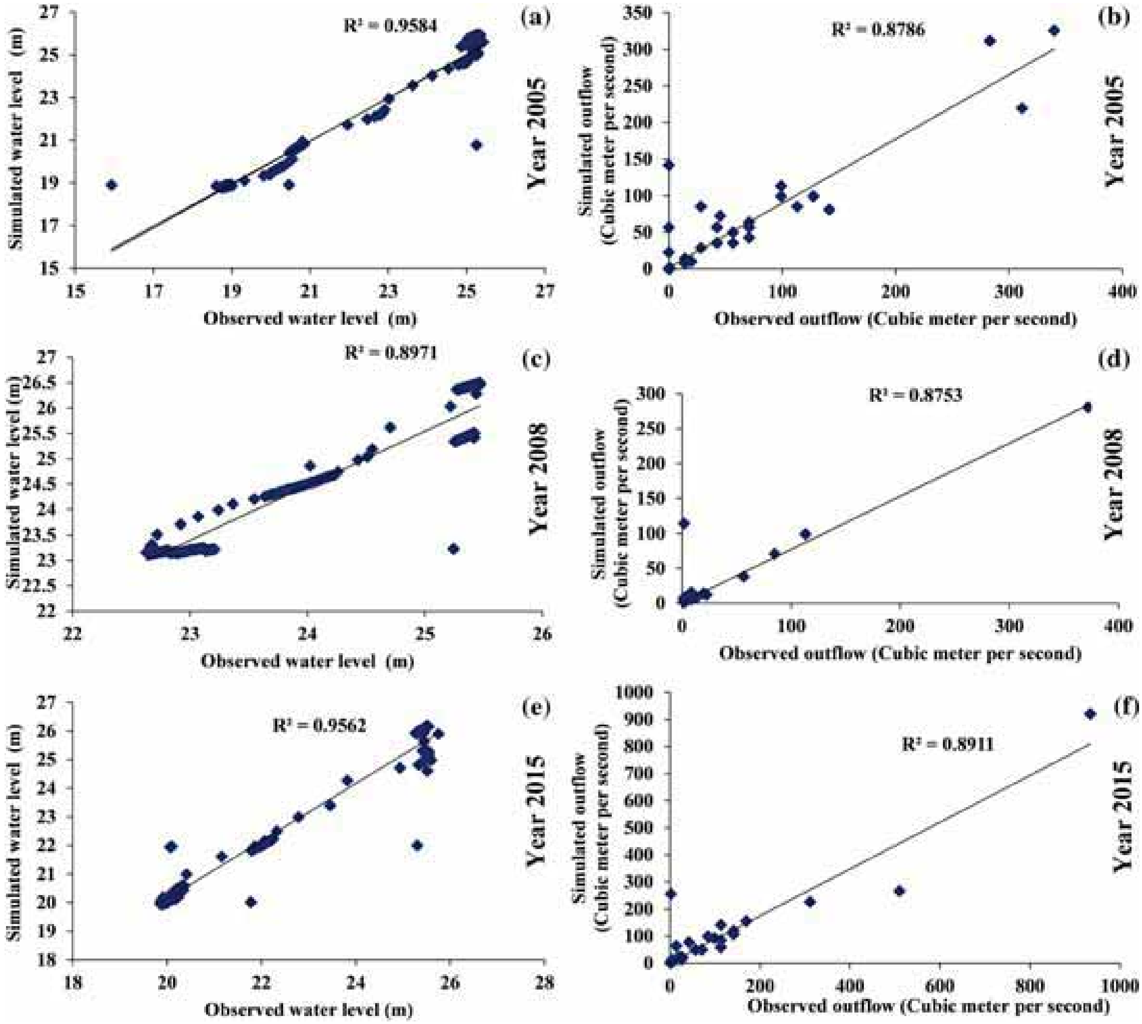

Figure 14. Comparison of simulated with observed water level and outflow during years 2005, 2008 and 2015 (actual case).

by 3 h in S2 when compared with S1 against the reduction of 3.655 Mm^3 storage from S1 to S2; whereas in S3 (figure 15, table 4), the outflow volume was reduced by about 37% from the S1 and the time to peak was delayed by 6 h from the inflow peak, as the initial storage was almost 50% of the reservoir. When the inflow of this event is considered in S3, it is possible to store all the inflow from the Chembarambakkam sub-catchment. S3 can help in mitigating the flood inundation extent downstream. In the case of the 2008 event, the duration, inflow to the reservoir and initial storage is comparatively larger than the 2005 flood event (figure 15b, table 4). Due to higher release at the beginning of the event, the outflow volume has been reduced and the time to peak was delayed by about 3–4 h. Changes in the instant of time to peak for outflow with all scenarios are more or less similar. Among these, S3 gives a better solution with 9% reduced volume than S2 and 3% reduced volume than S1. Although the reduced volume of outflow is less, it can be used to reduce the effects of downstream inundation to a significant amount. In the case of the extreme event of 2015 which was very large due to the inflow volume and shorter duration (figure 15c, table 4). In the case of the 2005 and 2008 events, S3 gives the best possible situation to reduce the outflow volume by 20.74% from S1 and 16.55% from S2. Even after reducing the initial storage to nearly 50% of the storage capacity, the outflow volume can be reduced only up to 20%, which shows the extremity of the event occurred in 2015. This reservoir can be used to mitigate the flood to a significant amount in terms of volume and by delaying the time to peak. Out of these events, only in the 2005 event S3 was very effective. As the inflow volume was huge in the 2008 and 2015 flood events, inundation could not have been avoided downstream but could have been minimised to a certain extent.

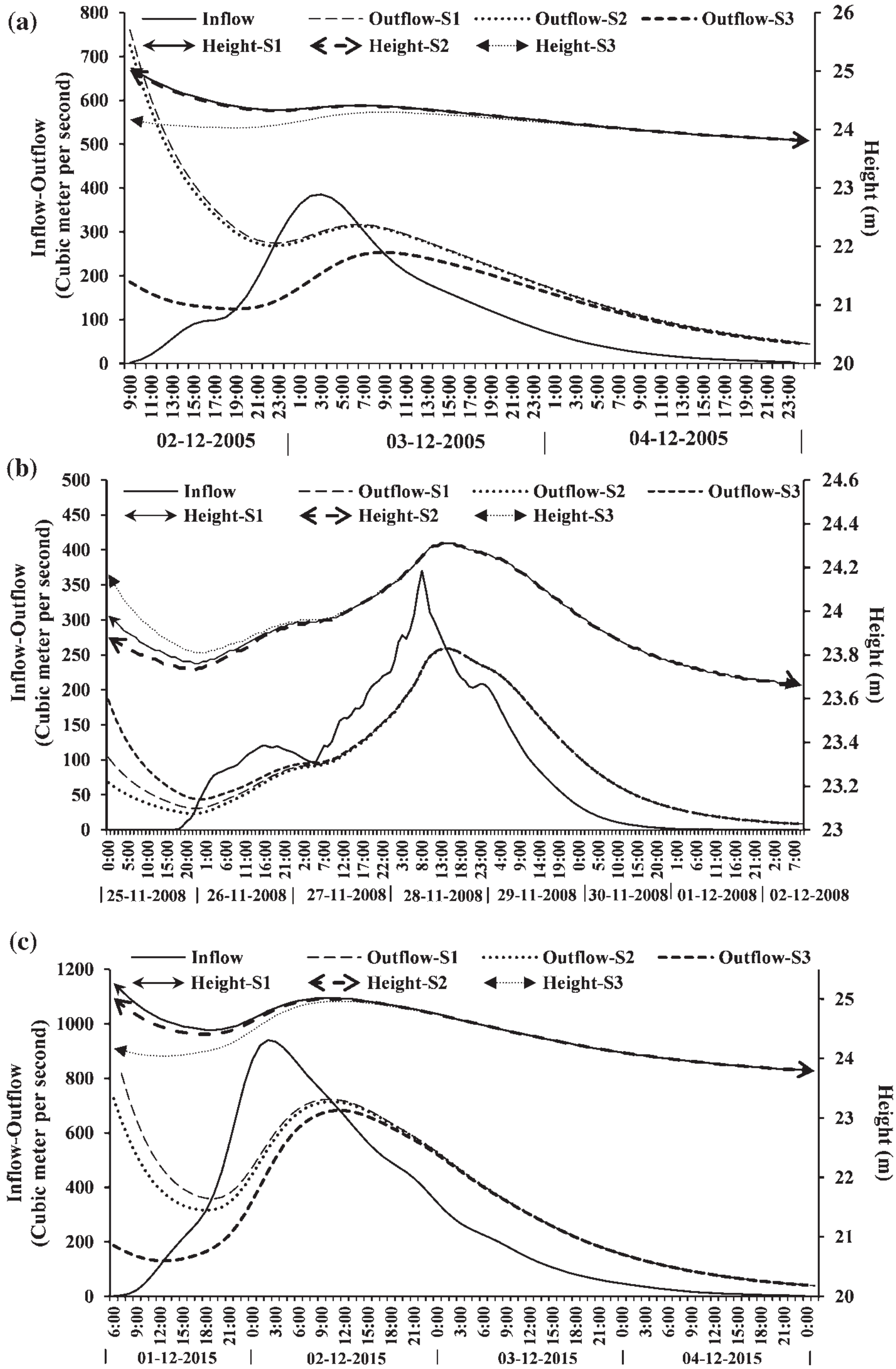

Figure 15. Comparison of simulated scenarios of operation of reservoir (**a**) 2005 event, (**b**) 2008 event and (**c**) 2015 event.

4. Conclusions

In this study, a box-model approach for reservoir operation under extreme conditions has been developed. The model has been used to estimate the volume of water to be released to achieve flood mitigation and to generate various combinations of outflow hydrographs. Also, it was used to determine the quantum of reduction in discharge to delay the time to peak. The performance of this box model was ascertained using the correlation coefficient and Nash–Sutcliffe efficiency with an average error estimation of 15% and 25% in water level, 21% and 18% in outflow simulation, respectively. The developed box-model approach can be employed for the daily water balance assessment as well as for the reservoir operation under different flow conditions. As this model predicts the outflow hydrograph, it can be used for the hydrologic and hydraulic models of the catchment in the

Table 4. *Comparison of performance of the reservoir during three different scenarios.*

Sl. no.	Event	2005	2008	2015
	Scenario one			
1	Instant of time to peak of outflow	03-12-05 @ 7:00	28-11-08 @ 13:00	02-12-15 @ 10:00
2	Inflow volume (Mm^3)	47.478	55.609	90.168
3	Outflow volume (Mm^3)	55.483	61.955	123.652
	Scenario two			
4	Instant of time to peak of outflow	03-12-05 @ 6:00	28-11-08 @ 14:00	02-12-15 @ 10:00
5	Inflow volume (Mm^3)	47.478	55.609	90.168
6	Outflow volume (Mm^3)	54.390	65.858	117.446
	Scenario three			
7	Instant of time to peak of outflow	03-12-05 @ 9:00	28-11-08 @ 13:00	02-12-15 @ 11:00
8	Inflow volume (Mm^3)	47.478	55.609	90.168
9	Outflow volume (Mm^3)	35.029	59.978	97.999

downstream for flood inundation studies and in early flood warning systems. Despite its simplicity, the box model is able to describe the hydraulic behaviour of the reservoir in terms of technical parameters such as water level and outflow. Although reservoir operation during extreme events is a complex problem, this simplified approach can be used by practicing engineers for better reservoir and flood management.

Acknowledgements

The authors would like to acknowledge the Anna Centenary Research Fellowship (Lr. No. CFR/ACRF/2016/42) received from Anna University, Chennai and Department of Science and Technology, Government of India (Grant No: Lr.No.INT/Italy/P-2/2016(ER) and DST/TM/WTI/WIC/2K17/82(G)).

References

Ahbari A, Stour L and Agoumi A 2019 Ability of the performance criteria to assess and compare reservoir management approaches; *Water Resour. Manag.* **33** 1541–1555.

Ahmad A, El-shafie A, Razali S F M and Mohamad Z S 2014 Reservoir optimization in water resources: A review; *Water Resour. Manag.* **28** 3391–3405.

Chang J, Guo A, Du H and Wang Y 2017 Floodwater utilization for cascade reservoirs based on dynamic control of seasonal flood control limit levels; *Environ. Earth Sci.* **76**(**260**) 1–12.

Cheng W M, Huang C L, Hsu N S and Wei C C 2017 Risk analysis of reservoir operations considering short-term flood control and long-term water supply: A case study for the Da-Han Creek Basin; *Water (Basel)* **9**(**424**) 1–23.

Coerver H M, Rutten M M and Van De Giesen N C 2018 Deduction of reservoir operating rules for application in global hydrological models; *Hydrol. Earth Syst. Sci.* **22** 831–851.

Doan J H 2003 *USACE, Geospatial Hydrologic Modeling Extension, HECGeoHMS: User's Manual*; Version 1.1, USACE, Davis, CA, USA.

Feldman A D 2000 *USACE (United States Army Corps of Engineers) hydrologic modeling system HEC-HMS: Technical reference manual*; USACE, Washington DC, USA.

Hsu N S, Huang C L and Wei C C 2015 Multi-phase intelligent decision model for reservoir real-time flood control during typhoons; *J. Hydrol.* **522** 11–34.

Huang W C and Hsieh C L 2010 Real-time reservoir flood operation during typhoon attacks; *Water Resour. Res.* **46**(**W07528**) 1–11.

Indian Meteorological Department, Chennai, http://www.imdchennai.gov.in/climate/chennai2.htm.

Kumar P, Tiwari K N and Pal D K 1991 Establishing SCS runoff curve number from IRS digital data base; *J. Indian Soc. Remote Sens.* **19**(**4**) 245–251.

Li N, Kinzelbach W, Li W P and Dong X G 2015 Box model and 1D longitudinal model of flow and transport in Bosten Lake, China; *J. Hydrol.* **524** 62–71.

Liu P, Li L, Guo S, Xiong L, Zhang W, Zhang J and Xu C Y 2015 Optimal design of seasonal flood limited water levels and its application for the Three Gorges Reservoir; *J. Hydrol.* **527** 1045–1053.

Raje D and Mujumdar P P 2010 Reservoir performance under uncertainty in hydrologic impacts of climate change; *Adv. Water Resour.* **33** 312–326.

Rouwet D and Tassi F 2011 Geochemical monitoring of volcanic lakes. A generalized box model for active crater lakes; *Ann. Geophys.* **54**(**2**) 161–173.

Saadatpour M, Afshar A and Edinger J E 2017 Meta-model assisted 2D hydrodynamic and thermal simulation model (CE-QUAL-W2) in deriving optimal reservoir operational strategy in selective withdrawal scheme; *Water Resour. Manag.* **31** 2729–2744.

Sakov P and Parslow J S 2004 Optimisation technique for calculating water transport in a box model (Gippsland Lakes, Victoria, Australia); *Estuarine Coast. Shelf Sci.* **59** 417–428.

Srinivasan V, Gorelick S M and Goulder L 2010 Sustainable urban water supply in south India: Desalination, efficiency improvement, or rainwater harvesting? *Water Resour. Res.* **46** W10504.

Uysal G, Schwanenberg D, Alvarado-Montero R and Sensoy A 2018 Short term optimal operation of water supply reservoir under flood control stress using model predictive control; *Water Resour. Manag.* **32** 583–597.

Velasquez J 2012 UNESCAP/UNISDR, (United Nations Economic and Social Commission for Asia and the Pacific/United Nations Office for Disaster Risk Reduction) reducing vulnerability and exposure to disasters; The Asia-Pacific Disaster Report 2012, Bangkok, Thailand UNESCAP/UNISDR.

Visentini M 1937 *The evapotraspiration from liquid surfaces* (Hydrological Memories and Studies), Publication n. 2 of the Italian National Hydrographic Service, Polygraphic National Institute, 9, Rome, Italy.

Corresponding editor: Subimal Ghosh