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ARTICLE

The projected changes in water status of the Mae Klong Basin, Thailand, using WEAP model

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Abstract
River basin management has become more dynamic and challenging due to increased competition among different water use sectors. Mae Klong Basin is rich in term of water availability, but increasing water demands in future due to inter-basin-based water management policy addressed by the national government may strongly influence the changes in water status. WEAP model was implemented to assess the current water supply and demand situations for this basin. Six different scenarios were established to evaluate the response of the basin to increasing demands under two SRES scenarios A2 and B2. The simulated results have shown that currently the water resources in the basin are sufficient to meet the existing needs in the wet season, but water shortage has occurred in the dry periods of 2014 and 2015 due to less rainfall in these years. The results have also shown that more water shortages have occurred under A2 scenario as compared to B2 scenario. Water shortages have occurred in all the developed scenarios indicating that the basin will face water scarcity particularly in the scenario five where transferring water to the adjoining area is difficult to possibly be implemented. The scenario six where a new hydropower project is proposed is considered feasible under both A2 and B2 scenarios and can help in meeting hydropower demands in the basin. It is pertinent to shape more effective policies and regulations in the basin for effective water resources management in reducing water shortage as well as achieving downstream water needs and power benefit in future.

Keywords Mae Klong Basin · WEAP model · Water resources management

Introduction

Efficient management of water resources has become more challenging due to increasing conflict among different water use sectors such as domestic, industrial, and agriculture. Population increase, economic development, and climate change are the main factors responsible for increased stress on water resources. Decisions to properly allocate water to different users have become very difficult.

In many water-stressed regions of the world especially in the agricultural countries like Thailand, balancing the water supply and water demand is not an easy task particularly in critical low flow period in which water supply from surface water sources is insufficient to reach the targeted water demand (Bejranonda et al. 2013). The Mae Klong Basin is one of the major river basins in Thailand which has some of the plentiful water resources. The Greater Mae Klong Irrigation Project (GMKIP) is the most water-intensive-use sector located in the lower portion of the basin.

Main challenges for effective water resources management include: response to increasing water scarcity, effective institutions that are responsible to farmer needs and can influence decision making, enforcement of policies and regulations, and effective cooperation and communication between all stakeholders (Biltonen et al. 2003). Future plan for the Mae Klong Basin includes allocating more water to Bangkok Metropolitan Waterworks Authority (MWA), Greater Mae Klong Irrigation Project (GMKIP), and water supply to Tha Chin Basin. The Electricity Generating Authority of Thailand (EGAT) has planned to construct

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another hydropower project downstream of Vajiralongkorn Dam. The Royal Irrigation Department (RID) has also planned to increase the minimum flow requirement downstream of Mae Klong Dam to meet the requirements of salinity control. Similarly, RID has projected to supply water from Srinagarind Dam to Uthai Thani Province at 1892 MCM per year. The effects of all these water demands were assessed through this study by establishing various scenarios in Water Evaluation And Planning (WEAP) model for the Mae Klong Basin.

Issues like allocation of scarce water resources, poor water quality, and need of policies for better water use and management are getting more attention. Simulation models focusing on water supply issues are not continuously satisfactory. Recently, an integrated or combined approach for water resources planning and development has emerged, which not only focuses on issues related to water demand but also pays attention to water quality and sustainability of the environment. WEAP is a software used to integrate these issues for planning of water resources and is developed by the Stockholm Environment Institute (SEI). The distinguishing feature of WEAP is that it adopts integrated approach for simulation of water resources systems through policy direction. On the demand side, WEAP addresses issues like patterns of water use, efficiencies for equipment, costs, water reuse, and demand for hydropower energy and allocation, while on the supply side, WEAP focusses on reservoirs, groundwater, streamflow, and water transfers. WEAP is a package for evaluating different alternatives for planning and management of water resources systems (SEI 2015). The basic principle of WEAP is mass balance. WEAP allocates water to water demands based on user-defined priorities. The heart of WEAP model is scenarios, through which it can answer what-if questions related to water supply and demand sides. WEAP tool has been used for many basins of the world as a support system for better water resources management (Lévite et al. 2003; Al-Omari et al. 2009, 2015; Hoff et al. 2011; Swiech et al. 2012; Hamlat et al. 2013; Ali et al. 2014; Demertzi et al. 2014; Shumet and Mengistu 2016). In this study, the WEAP model was implemented for the Mae Klong Basin with the objectives of evaluating the current availability of water resources and to investigate the change of projected water supply and water demands for better water management in future.

Methods

Study area

The Mae Klong River Basin has an area of 30,167 km^2 and lies in the west of Thailand along the Myanmar border (Fig. 1). Out of the 25 major river basins in Thailand, the Mae Klong Basin has abundant water resources which are vital to the national economy of the country. It is fed by two tributaries; Khwae Yai and Khwae Noi Rivers. Two large dams were constructed on these tributaries, i.e., Srinagarind Dam on the Khwae Yai River and Vajiralongkorn Dam on the Khwae Noi River. Tha Thung Na Diversion Dam was later constructed on the downstream side of Srinagarind Dam to reregulate downstream flow before discharging to Mae Klong Diversion Dam constructed on the Mae Klong River at Tamuang district in Kanchanaburi Province. In 1983, the Electricity Generating Authority of Thailand has initially studied to propose the new dam downstream of Vajiralongkorn Dam called "Ban Junday Dam" which was approved by the government in 2013 and will be completed in 2018 (Fig. 2).

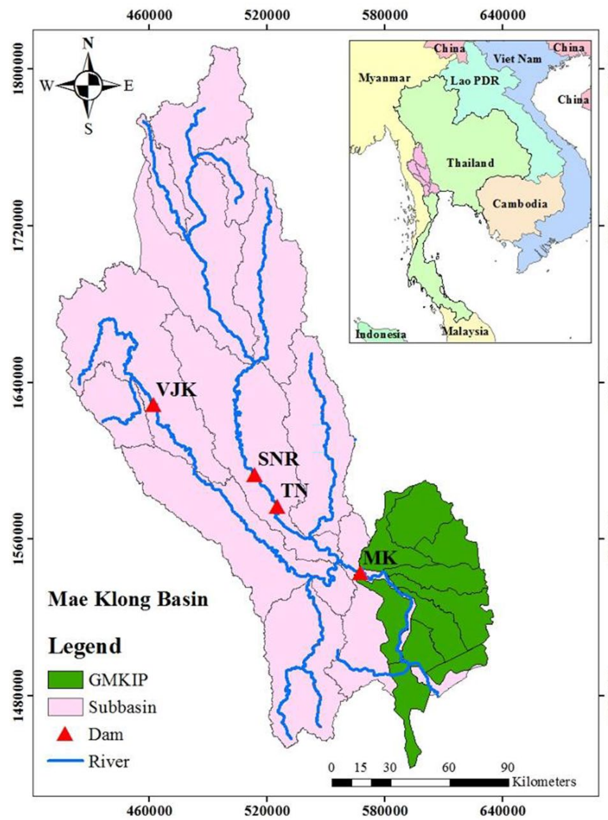


Fig. 1 Mae Klong Basin

The downstream area of the basin is more intensive in terms of water usage. It is composed of urbanized areas near the river as well as the Greater Mae Klong Irrigation Project, one of the largest irrigation areas in Thailand. The water is mainly used for agriculture, domestic, and industrial use, hydropower, and salinity control toward the gulf of Thailand (Kasetsart University 2016). Administratively, the Mae Klong Basin can be divided into 25 districts belonging to 8 provinces. Around 70% of the basin area is composed

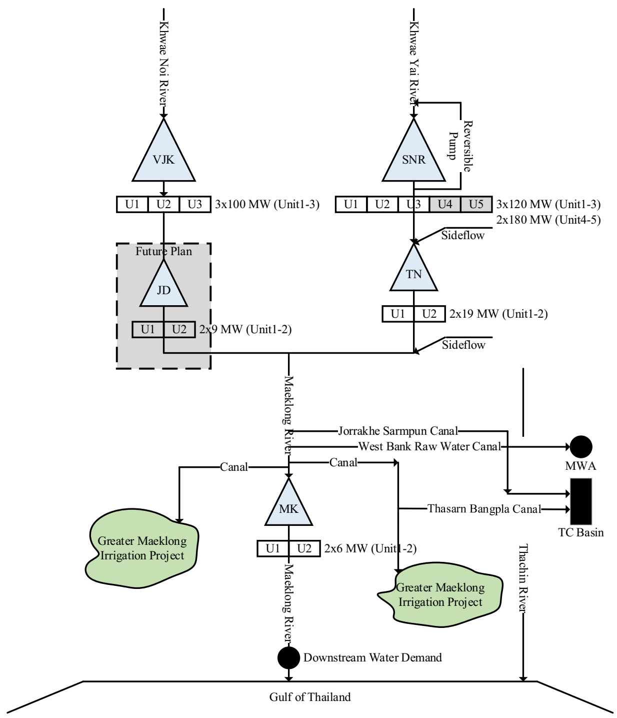


Fig. 2 Schematic of reservoir systems in the Mae Klong Basin

of three provinces, namely: Kanchanaburi, Ratchaburi, and Samut Songkhram. The forest and agriculture cover 73 and 19% of the basin area and 3% of the entire basin is covered by water bodies (Vongvisessomjai 2005).

The Electricity Generating Authority of Thailand has been authorized to control all structures of three main dams: Srinagarind (SNR), Vajiralongkorn (VJK), and Tha Thung Na (TN) Dams and operate water supply in reservoirs. Mae Klong Dam (MK) is under the control of RID. However, the coordination at departmental levels between EGAT and RID has been carried out by creating the seasonal plan of agricultural water needs which will be used for release determination from upper reservoirs. Allocating water in main irrigation system and satisfying downstream water needs at Mae Klong Dam are accomplished by RID (Biltonen et al. 2003).

Most rainfall in the watershed is caused by the southwest monsoon, which would normally begin to rise from May to October. The average annual rainfall in the basin lies between 980 and 1918 mm per year from the long-term record. For the rain outside the influence of the southwest monsoon, it rains from the northeast monsoon in December, January, and February, but the amount of rainfall is very little and cannot be used for agriculture much (Kasetsart University 2016). Runoff comes from two main rivers: Khwae Yai and Khwae Noi Rivers. The Khwae Yai River has a length of about 450 km and a catchment area of 14,630 km^2. The Khwae Noi River is about 320 km and a catchment area of 10,690 km^2.

The Greater Mae Klong Irrigation Project has an irrigation service area of 4800 km^2 comprising 10 irrigation subprojects. In 2006, the total command area was 5301 km^2, and 91% was supplied by two-dam water sources; Srinagarind and Vajiralongkorn Reservoirs. The main crops are paddy, which is cultivated on two-thirds of the total area, and sugarcane, which is cultivated on one-third of the area. The Mae Klong Dam serves as headworks for GMKIP, where the water is diverted for irrigation through right and left canals. Continuous delivery of water with control in the upstream is the water delivery method for GMKIP. Majority of canals are lined with concrete to reduce seepage of water and consequently reduce water conveyance losses (Vudhivanich et al. 2002).

Application of WEAP model for the Mae Klong Basin

Input data in WEAP model

Monthly rainfall data were collected from the Royal Irrigation Department (RID) and Thai Meteorological Department (TMD) for the year 2000–2015 as shown in Fig. 3a. Eight rainfall stations were considered for the rainfall-runoff modeling based on data availability. Missing rainfall data were filled from nearby stations based on their correlations. The consistency of rainfall data was checked using double-mass analysis. The monthly rainfall data for the period 2000–2015 were used in WEAP model for rainfall-runoff modeling, and the average monthly data are shown in Fig. 4. The vector-layered data for the Mae Klong Basin were analyzed in ArcGIS. The basin was divided into six sub-basins for the purpose of rainfall-runoff modeling in WEAP. Runoff data were collected from RID for six gauge stations as shown in Fig. 3b. The average monthly flows for all the six gauges are shown in Fig. 5. Land use data for the Mae Klong Basin were obtained from the Land Development Department (LDD), Thailand. These data were analyzed in ArcGIS and classified into different land use types as shown in Fig. 3c. RID has published crop coefficients for 40 crop varieties in Thailand (RID 2011a) and was used in this study. Crop coefficients for other crop uses were considered following the work of Ingol-Blanco and McKinney (2012). The reference evapotranspiration (ETo) data obtained from RID were verified by using freely available FAO's ETo calculator. The results of ETo for one station are given in Table 1. Data on effective precipitation for the Mae Klong Basin were also obtained from RID and converted into percentages for rainfall-runoff modeling in WEAP model.

In implementing WEAP model for the Mae Klong Basin, water demands were identified based upon the irrigation requirements in GMKIP and water transfer to neighboring

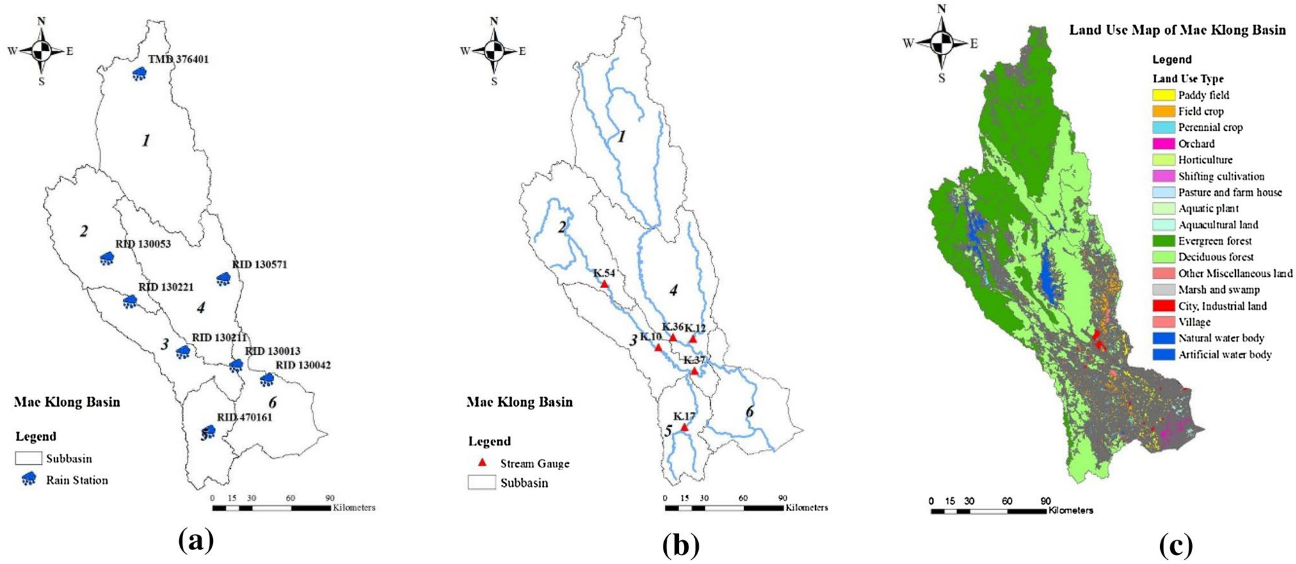


Fig. 3 Input data used in WEAP model. **a** Rainfall stations, **b** Basin division and streamflow gauge stations, **c** land use map

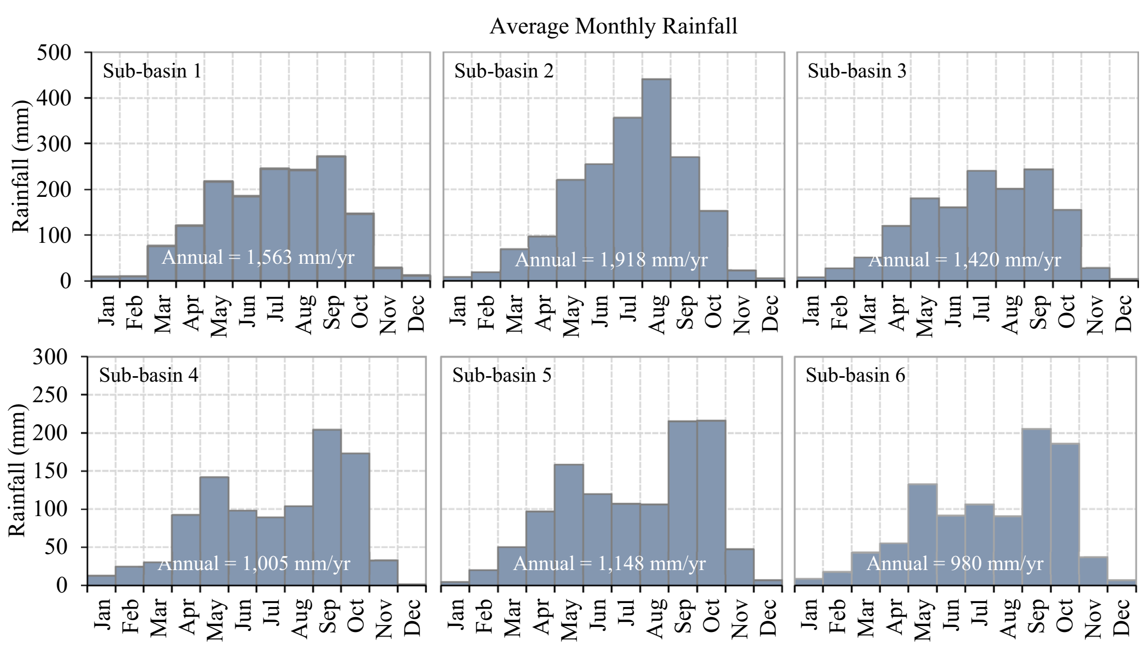


Fig. 4 Average monthly rainfall from 2000 to 2015 in the Mae Klong Basin

basin. Water is supplied to 10 irrigation subunits of GMKIP. Two subunits Thamaka and Ratchburi right bank (RB) are located on the right side of the Mae Klong River, whereas Banglen, Damnoen Saduak, Khamphaeng Saen, Nakhon Pathom, Nakhonchum, Phanomthuan, Ratchaburi left bank (LB), and Song Phi Nong are located on the left side of Mae Klong Dam. Water is supplied to these irrigation subunits through five demand site nodes, two on the right side (GMKIP_1R and GMKIP_2R) and three on the left side of the Mae Klong River (GMKIP_1L, GMIP_2L and GMKIPLP). Water is diverted to Tha Chin Basin through Thasarn Bangpla (TSBP) and Jorrakhe Sarmpun (JKSP) canals to two demand sites, and to the Bangkok Metropolitan Water Works Authority (MWA). Water is pumped from downstream of Srinagarind Dam back to the reservoir and is represented by demand site (SNR_pump) in WEAP model. The total annual water demands in the basin are 7420 MCM

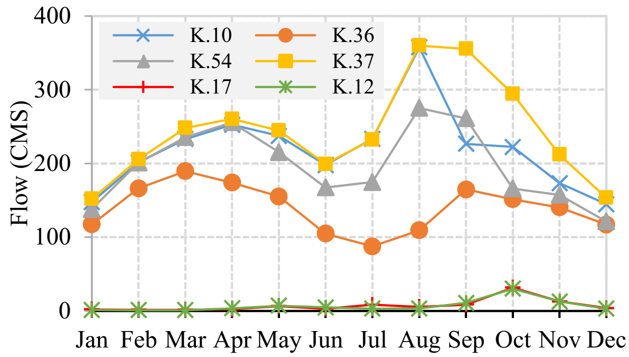


Fig. 5 Average monthly streamflow from 2000 to 2015

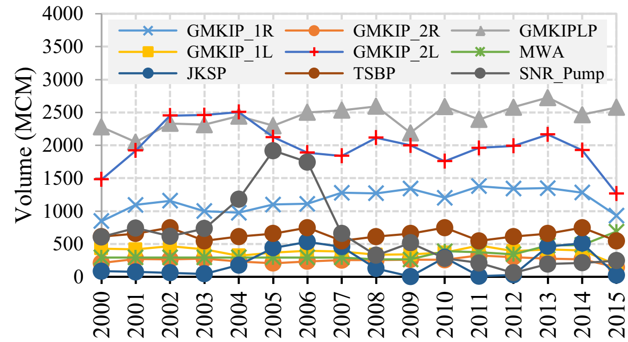


Fig. 6 Total annual water demands from 2000 to 2015

per year as shown in Fig. 6. The monthly data for the period 2000–2015 were input in demand sites in WEAP model.

WEAP schematic for the Mae Klong Basin

The schematic of the WEAP model for the Mae Klong Basin is shown in Fig. 7. Supply of water from reservoirs to demand sites in the WEAP model was generally done based on specified priorities. In this study, setting water allocation priorities for different water demands in the Mae Klong Basin was referred to the joint operating policy of RID and EGAT as follows: 1 for minimum flow requirement and water supply to MWA, 2 for irrigation demands, 3 for hydropower production and water transfer to the Tha Chin Basin, and priority for reservoir filling was set as 3 for Tha Thung Na and Mae Klong Dams and 4 for Srinagarind and Vajiralongkorn Dams, respectively.

Rainfall-runoff modeling in WEAP

Different methods are available in WEAP for rainfall-runoff modeling of the basin, which include rainfall-runoff (simplified coefficient method), irrigation demands only (simplified coefficient method), rainfall-runoff (soil moisture method), MABIA (FAO 56, dual KC, daily), and plant growth (daily; CO_2, water and temperature stress effects). Based on data availability for the Mae Klong Basin, rainfall-runoff with simplified coefficient method was employed for this case study based upon the hydrological processes in water cycle as shown in Fig. 8.

The parameters which can be used for model calibration in WEAP using rainfall-runoff (simplified coefficient method) include runoff coefficient, crop coefficient, reference crop evapotranspiration, and effective rainfall. The model calibration was done manually for these parameters. The calibrated values for the runoff coefficient for the six sub-basins were estimated by dividing the runoff generated from rainfall into surface runoff (comparing with the observed streamflow data) and groundwater infiltration. Then, the crop coefficients for each land use were calibrated followed by ETo and effective rainfall to match the simulated results with the historical streamflow data. The calibrated values for the runoff coefficients for the six sub-basins are given in Table 2.

The infiltration coefficients estimated in this study can be compared with Biltonen et al. (2003) for lower sub-basins (5 and 6) due to the similarity in the sub-basin areas for both studies. Their values for infiltration coefficients are 0.84 and 0.686 for sub-basin 5 and 6, respectively. JICA (1997) also reported a runoff coefficient of 0.30 for the Lampachi and Mae Klong Plain. The calibrated values of crop coefficients for different land uses are given in Table 3.

Water demands for GMKIP were calculated using FAO's CROPWAT 8.0 (Food and Agriculture Organization of United Nations 1999), and the potential cropping patterns and planting times in 2013 were selected to estimate crop water. In 2013, the main crops were sugar cane, rice, mango, pomelo, and vegetables as shown in Table 4. The crop period for in-season rice is from May to September. The off-season rice has two crop periods from March to July and November to March. The monthly crop water requirements for these main crops are shown in Fig. 9. Water demand data for diversion to Tha Chin Basin through TSBP and JKSP canals were obtained from RID, and MWA demand data were obtained from MWA office in Bangkok. Hydropower

Table 1 Reference crop evapotranspiration (ETo) values calculated by using ETo calculator *Source:* RID (2011b)

Kanchanaburi, Thailand	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. ETo (mm/day)	3.4	4.3	5.0	5.3	4.7	4.3	4.3	4.2	3.9	3.4	3.2	3.3

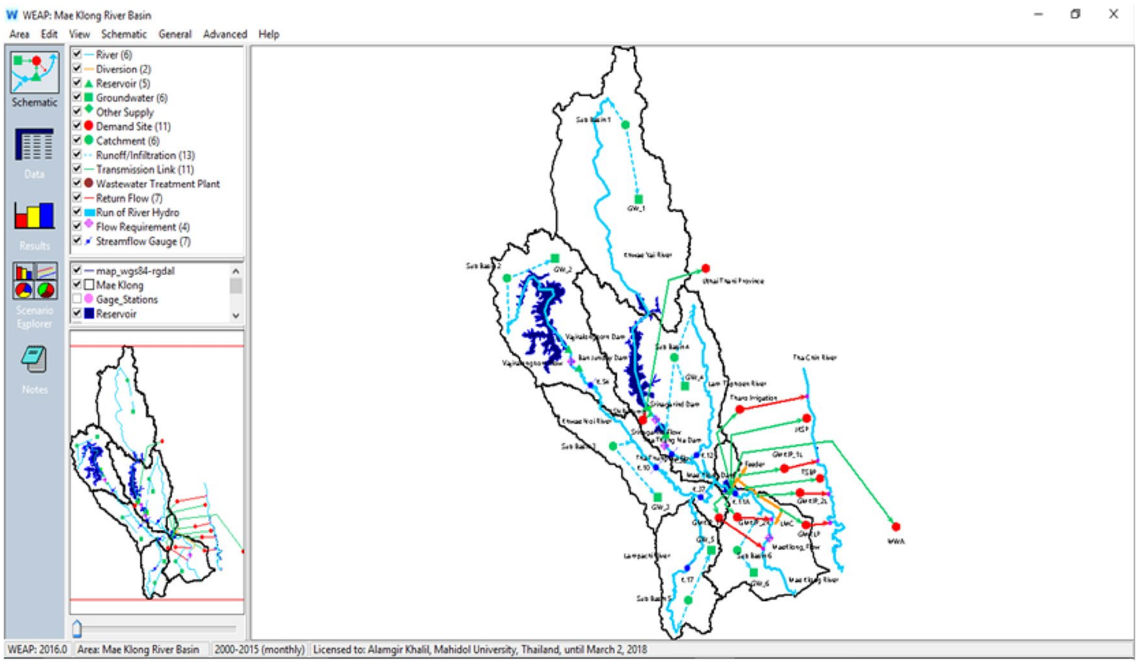


Fig. 7 Schematic of the Mae Klong Basin in WEAP model

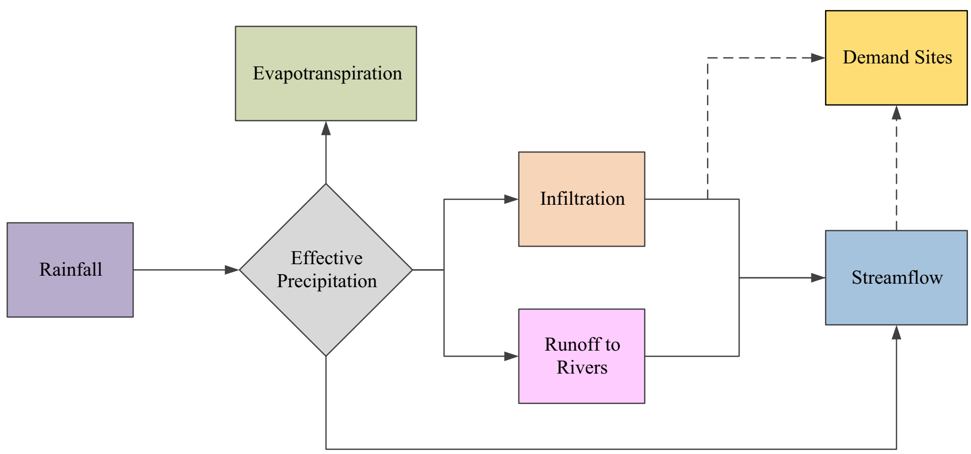


Fig. 8 Flowchart of rainfall-runoff submodel with simplified coefficient method. *Source:* LeRoy (2005)

Table 2 Calibrated runoff coefficients

Sub-basin	Area (km^2)	Runoff coefficient	Infiltration coefficient
1	8818.31	0.65	0.35
2	5047.50	0.80	0.20
3	3381.18	0.40	0.60
4	6535.62	0.37	0.63
5	2547.16	0.20	0.80
6	3836.89	0.30	0.70

demands data for Srinagarind, Vajiralongkorn and Tha Thung Na Dams were obtained from EGAT, whereas RID provided the hydropower data for the Mae Klong Dam.

The return flows from the irrigation projects on the right side of Mae Klong River supply water to the river downstream of Mae Klong Dam, while return flows from irrigation projects on the left side is a major water supply for the Tha Chin River since most of the drainage on the left side of GMKIP flows into Tha Chin River. These return flows are estimated as 70% on the right side and 30% on the left side of GMKIP (Kulsuwan 1999).

For an assessment of climate variability of the Mae Klong Basin, the years from 2000 to 2015 were classified as wet, dry, or normal years as shown in Fig. 10. Data from the eight rain gauges were used to compute the mean annual rainfall for the period 2000–2015 using arithmetic mean method. The hydrological method suggested by Yoo (2006) was used

Table 3 Crop coefficients for different land uses used in the hydrologic model

land use	Total area (km^2)	Total area (%)	Kc
Paddy field	978.11	3.24	1.30
Field crop	3153.94	10.46	1.01
Perennial crop	1170.41	3.88	1.10
Orchard	824.24	2.73	1.20
Horticulture	221.36	0.73	1.13
Shifting cultivation	199.01	0.66	0.88
Pasture and farm house	111.09	0.37	0.49
Aquatic plant	1.28	0.00	0.90
Aquaculture land	248.41	0.82	0.90
Evergreen forest	9992.42	33.12	0.35
Deciduous forest	10,559.30	35.00	0.38
Other miscellaneous land	718.52	2.38	0.90
Marsh and swamp	26.68	0.09	0.90
Urban	428.83	1.42	0.77
Villages	596.70	1.98	0.80
Water	935.72	3.10	1.00

for classification of normal, wet and dry years for the Mae Klong Basin. Periods in which annual basin precipitation is more than *P*mean + 0.75SD ($P \geq P$mean + 0.75SD) can be considered as the wet years, whereas periods with annual basin precipitation less than *P*mean—0.75SD can be considered as the dry years ($P \leq P$mean − 0.75SD). Periods with annual basin precipitation of more than *P*mean − 0.75SD but less than *P*mean + 0.75SD can be considered as the normal years (*P*mean − 0.75SD < *P* < *P*mean + 0.75SD) as shown in Fig. 10.

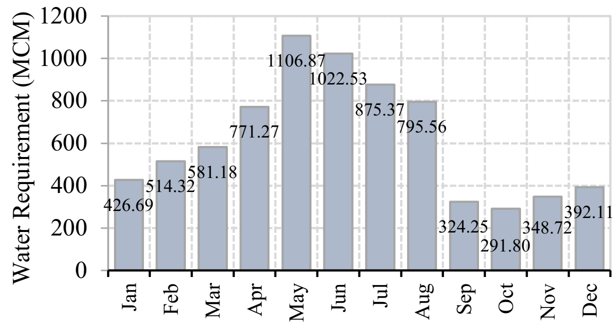


Fig. 9 Crop water requirements for various crops in GMKIP in 2013

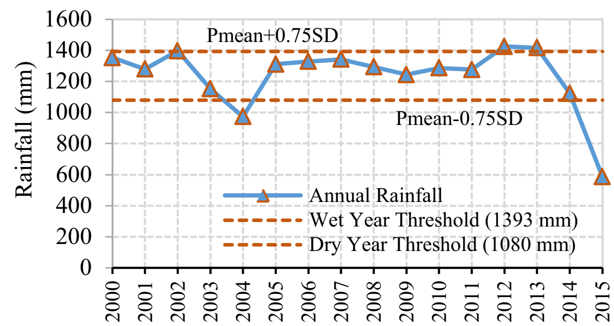


Fig. 10 Normal, wet, and dry years for the Mae Klong Basin

Scenarios setting

(1) Considering Water Supply Side Conditions

Shrestha (2014) predicted rainfall anomalies for the Mae Klong Basin using data from a Regional Climate Model (PRECIS) for two SRES scenarios A2 and B2 for the near future 2020s (2011–2040). It was reported that the projected

Table 4 Irrigated areas for main crops in GMKIP in 2013

Sub-irrigation project	Irrigated area (km^2)						
	In-season rice	Sugarcane	Mango	Pomelo	Vegetable	Off-season rice	
						Crop-1	Crop-2
Song Phi Nong	181.71	281.93	4.36	2.36	54.04	186.71	0.00
Banglen	251.82	117.73	18.61	8.60	13.72	251.82	0.00
Khamphaeng Saen	158.94	110.16	11.48	2.24	124.64	0.00	158.94
Phanomthuan	183.23	218.42	6.01	6.65	83.03	0.00	185.12
Thamaka	368.33	40.04	10.68	0.34	35.95	172.15	177.73
Nakhon Pathom	65.21	40.61	139.74	22.30	141.04	0.00	64.42
Nakhonchum	74.94	24.37	102.80	0.00	25.85	12.86	46.66
Ratchaburi Left Bank	92.25	8.73	88.48	6.24	14.33	0.00	67.99
Ratchaburi Right Bank	276.00	0.00	102.88	0.00	18.40	0.00	230.08
Damnoen Saduak	8.94	0.00	98.70	0.00	9.85	8.94	0.00
Total	1661.36	842.00	583.73	48.73	520.86	632.47	925.95

rainfall anomalies for the near future 2020s are − 4.2% for A2 and − 6.6% for B2 for the dry period (Nov.–Apr.) and 7.2% for A2 and 10.9% for B2 for the wet period (May–Oct.). Therefore, rainfall data in the WEAP model for the future period 2016–2030 were prepared for A2 and B2 Scenarios using the projected anomalies. It can signify that A2 scenario represents moderate economic growth, very high population increase, and focusing on self-reliance and local identity. B2 scenario represents slow economic growth, low population increase, focusing on environmental sustainability, and regional solutions to environmental issues.

(2) Considering Water Demand Side Conditions

The basic benefit of WEAP model is to develop scenarios that are inherited from reference scenario. Scenarios are plausible future conditions to see the effect of changing supply and demand conditions. These scenarios can answer what-if questions. In this study, six scenarios were developed taking into account different factors and according to RID policies, which may affect the water resources availability in the Mae Klong Basin for the next 15 years (2016–2030). The six scenarios considered are:

- Scenario 1: Increased irrigation demand 15% of the irrigated area of (5215) km^2 (3,259,441 rai) cultivated in 2013.
- Scenario 2: Increased MWA demand 65% of the 352 MCM per year from 0.8 (MCM) per day into 1.2 (MCM) per day.
- Scenario 3: Increased minimum downstream flow requirement at Mae Klong Dam into 80 CMS to reduce the impact of salt intrusion at the estuary.
- Scenario 4: Increased Tha Chin Basin demand 10% of the existing 849 MCM per year.
- Scenario 5: Water transfer to Uthai Thani Province (1892 MCM per year) and Tharo Irrigation (607 MCM per year).
- Scenario 6: Adding a re-regulated dam, Ban Junday (BJ) downstream of Vajiralong Dam to supplement the hydropower benefit according to the power development plan of EGAT.

Results and discussion

Calibration and validation of WEAP model

Calibration

Calibration of a model refers to changing the parameters so that the simulated results are closely matching the observed data. The data available for WEAP model for the Mae Klong Basin are from 2000 to 2015. Calibration period was taken during 2000–2010. The WEAP model was calibrated at eight gauges in the basin. These eight gauges include inflows to Srinagarind and Vajiralongkorn Dams; K.54, K.10, and K.37 located on the Khwae Noi River; K.17 located on the Lampachi River; K.12 located on the Lam Taphoen River; and K.36 located on the Khwae Yai River. The calibration results are shown in Fig. 11.

To evaluate the performance of the calibration results, the statistical parameters considered for this study were percent bias (PBIAS), Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), Pearson correlation coefficient (r), index of agreement (d), the ratio of root-mean-square error to the observations standard deviation (RSR), and volumetric efficiency (VE) as expressed in the following equations (Moriasi et al. 2007).

Percent bias (PBIAS):

$$\text{PBIAS} = 100\frac{\sum_{i=1}^{N}\left(O_i - S_i\right)}{\sum_{i=1}^{N} O_i}. \tag{1}$$

Nash–Sutcliffe efficiency (NSE):

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{N}\left(O_i - S_i\right)^2}{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2}. \tag{2}$$

Index of agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{N}\left(O_i - S_i\right)^2}{\sum_{i=1}^{N}\left(\left|S_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2}. \tag{3}$$

Ratio of RMSE to the standard deviation of the observations (RSR):

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \frac{\sqrt{\sum_{i=1}^{N}\left(O_i - S_i\right)^2}}{\sqrt{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2}}. \tag{4}$$

Volumetric efficiency (VE):

$$\text{VE} = 1 - \frac{\sum_{i=1}^{N}\left|S_i - O_i\right|}{\sum_{i=1}^{N}\left(O_i\right)}. \tag{5}$$

where O_i is the ith value of the observed data, S_i is the ith simulated value, N is the total number of observations, $\bar{O}$ is the mean of the observed data

According to Moriasi et al. (2007), the model performance is in general satisfactory if PBAIS is ± 25% for streamflow, NSE > 0.50 and RSR ≤ 0.70. The range for R^2,

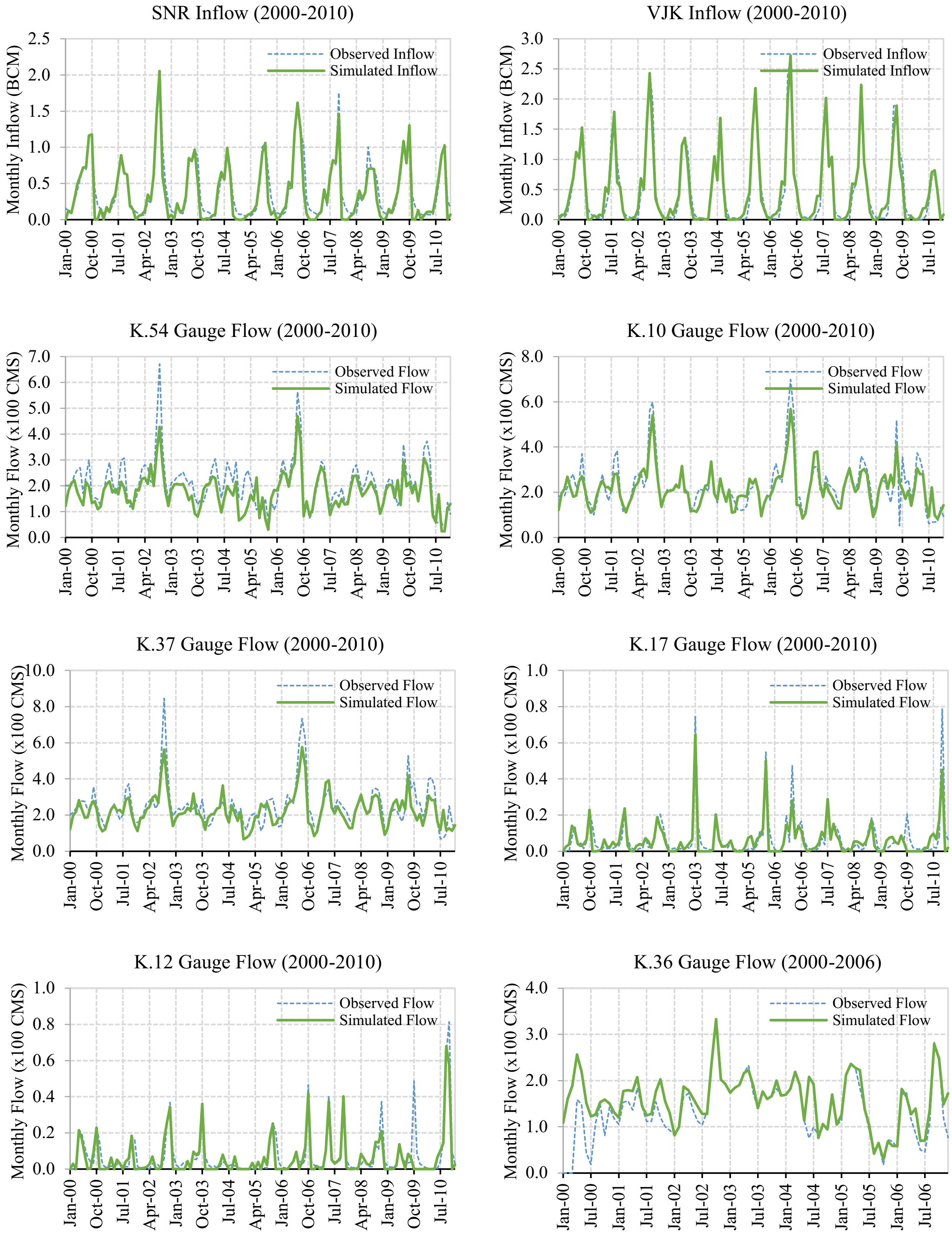


Fig. 11 Calibrated flows obtained from WEAP model for the Mae Klong Basin

r, d, and VE is 0–1, with 1 being perfect agreement between observed and simulated values. As is clear from Table 5, all the statistical parameters are within the desirable ranges indicating that the model simulations reasonably agree well with the observed data.

Table 5 Performance statistics for calibration and validation results

Gauges	Statistics						
	(PBIAS)	NSE	R^2	RSR	*r*	*d*	VE
Srinagarind reservoir inflow	− 10.7	0.89	0.91	0.33	0.95	0.97	0.8
Vajiralongkorn reservoir inflow	− 0.1	0.96	0.96	0.2	0.98	0.99	0.83
K.54	− 14	0.62	0.74	0.67	0.86	0.88	0.79
K.10	− 4.6	0.77	0.79	0.48	0.89	0.93	0.85
K.37	− 10.4	0.66	0.71	0.58	0.85	0.89	0.8
Lampachi River flow (K.17)	− 10.8	0.79	0.8	0.46	0.89	0.93	0.53
Lam Taphoen River flow (K.12)	− 15.8	0.75	0.76	0.5	0.87	0.93	0.56
K.36	13.6	0.63	0.74	0.61	0.86	0.9	0.85

Validation

Validation is the process of running the model with an independent set of data and comparing the simulated results with the observed data. If the simulated results closely match the observed data, then the model is calibrated. Validation results for the period 2011–2015 are shown in Fig. 12. The simulated results for validation period reasonably well agree with the observed data. Performance statistics of the validation results are shown in Table 6. The statistical parameters are within desirable ranges for all the gauges except K.10 gauge. For K.10, the R^2 value is 0.46, indicating that 46% of the variance in observed data is explained by the model. The value of RSR is 0.75, which is slightly above the satisfactory limit of 0.70.

Simulated reservoir storages

Comparison of the four-reservoir simulated storages with the observed storages is shown in Fig. 13. It is found that the simulated reservoir storages can resemble closely the observed storage particularly at two diversion dams: TN and MK. However, using the revised reservoir rule curve developed in 2005 for long-term simulation of SNR and VJK storage dams may cause a highly deviated value in storages especially before 2005 at SNR dam. All in all, the values of the statistical parameters indicate good agreement between the simulated and observed results as given in Table 7.

According to the constant patterns in both long-term observed storage and simulated storage of SNR and VJK dams which reflect water availability in the basin as well as reservoir operation strategy performed, it can guarantee that the quantity of water supply in the Mae Klong Basin is not much deviated and remains stable. Moreover, the results of stationary test of two sets of net water storages are reconfirmed that there is no significant change in term of water supply stored in two reservoirs due to operating policy used and incoming flows.

Reference scenario

“Current Accounts” serve as the starting year of the simulation period in WEAP for all the scenarios. It provides the basic definition of the current water system. The year 2000 was selected as the current accounts in WEAP model. After current accounts, reference scenario also called “Business-as-usual” was established to evaluate the existing water situation in the study area based on current hydrological, social, and technological trends. The reference scenario was developed for the period 2001–2015, and the unmet demands obtained from WEAP are shown in Fig. 14. It showed the small values of the average unmet demand of 62 MCM per year for agriculture, and 17 MCM per year for the Tha Chin Basin demand. However, the water supply demand by MWA was fully met. The results obtained from reference scenario also indicated that the unmet water demands in the Mae Klong Basin have started in December 2014 and continued in 2015 which can be attributed to the significant decrease in rainfall trend after 2013 as shown in Fig. 10. The total unmet demand in 2014 is 399 MCM and in 2015 is 781 MCM, indicating that the Mae Klong Basin has already started to face water shortages particularly in the dry season. It is illustrated that allocating water at Mae Klong Dam during 2001–2015 was carried out according to the specified priorities in accomplishing agricultural water demand and minimum flow requirements firstly. Therefore, their reliability is very close to 100% as appeared in Fig. 15. However, it showed the slight decrease in reliability ranging between 84.90 and 96.90% for hydropower generation of four main dams since hydropower is considered as a secondary purpose for operation.

Projected results

Reference scenario during 2016–2030

The hydrologic model of Mae Klong Basin developed in WEAP was extended up to 2030 under the two SRES scenarios A2 and B2 and the results are shown in Figs. 16, 17, 18

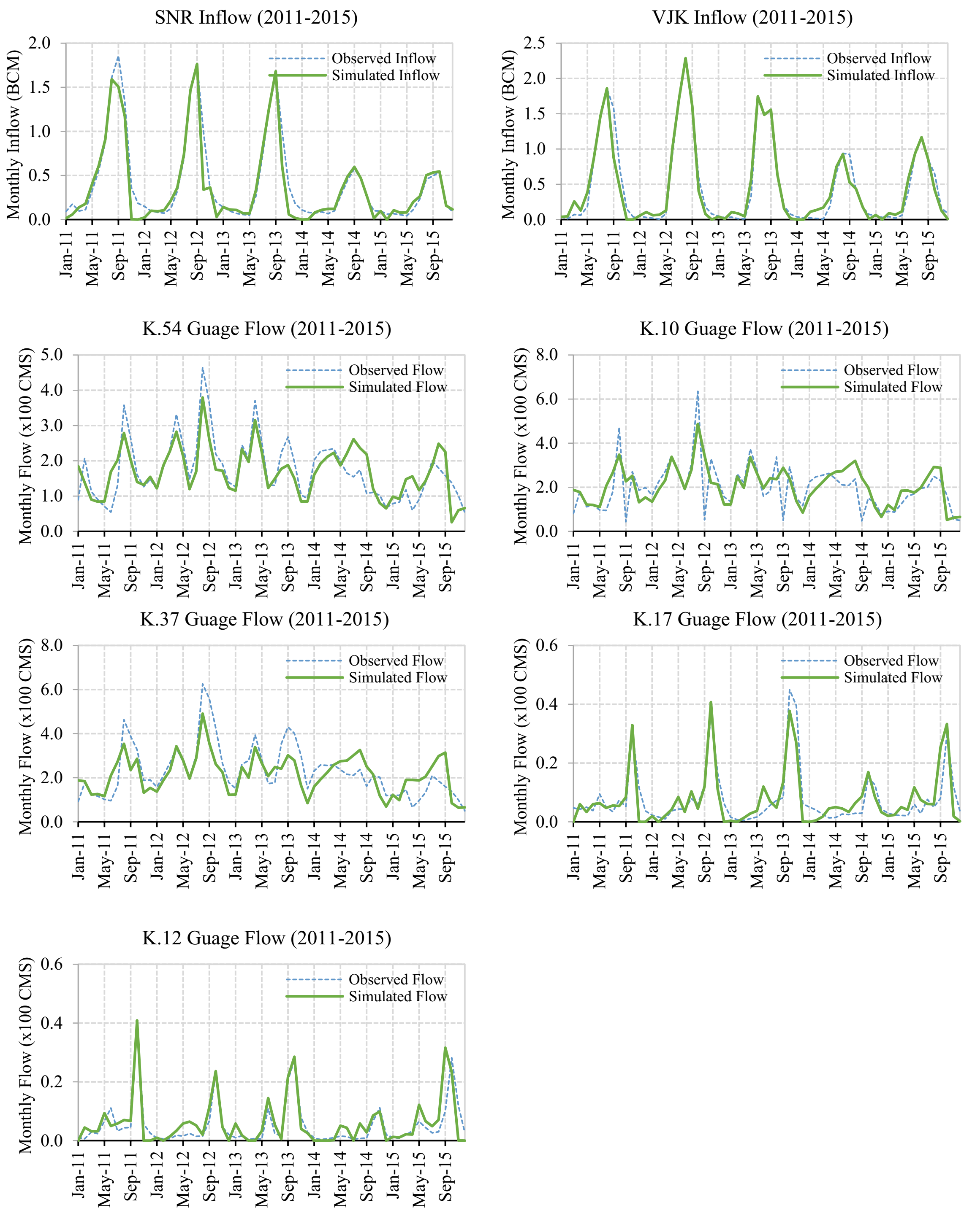


Fig. 12 Validated flow obtained from WEAP model for the Mae Klong Basin

and 19. Water shortages have occurred in A2 scenario, but all the demands are met under B2 scenario. For A2 scenario, the total unmet demand for agriculture is 1.12 MCM per year, for the Tha Chin Basin is 0.18 MCM per year, whereas MWA demand is fully met. The hydropower reliability is in the range of 95.83–100% for the dams under A2 scenario, whereas under B2 scenario, it is 96.35–100%. The minimum flow requirements downstream of the dams are almost fully met under both scenarios. These results showed that water shortages in the near future can be managed through effective water resources planning in the basin.

Table 6 Performance statistics for validation results

Gauges	Statistics						
	(PBIAS)	NSE	R^2	RSR	r	d	VE
Srinagarind Reservoir inflow	− 8.3	0.92	0.92	0.29	0.96	0.98	0.81
Vajiralongkorn Reservoir Inflow	− 1	0.95	0.95	0.23	0.97	0.99	0.83
K.54	− 2.9	0.64	0.64	0.59	0.8	0.88	0.78
K.10	5.6	0.43	0.46	0.75	0.68	0.81	0.72
K.37	− 5.5	0.54	0.55	0.67	0.74	0.83	0.73
Lampachi River Flow (K.17)	− 0.9	0.76	0.77	0.49	0.88	0.93	0.56
Lam Taphoen River Flow (K.12)	16.5	0.71	0.77	0.54	0.88	0.93	0.5

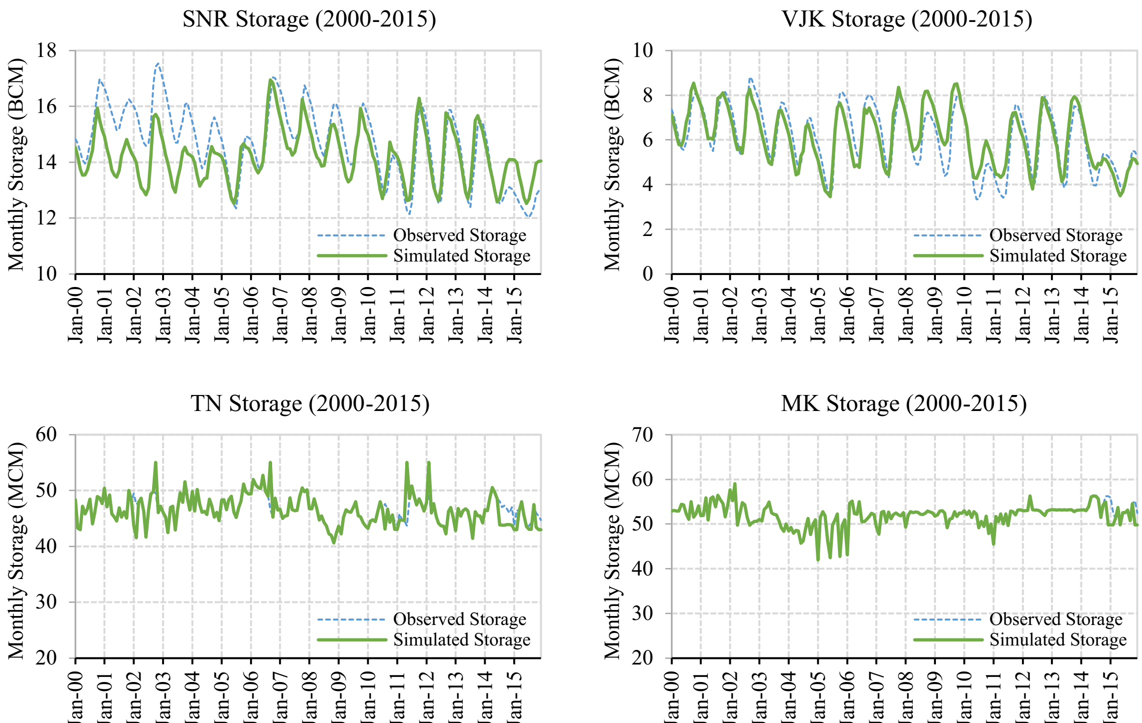


Fig. 13 Comparison of the simulated reservoir storages with observed storages

Table 7 Performance statistics on the reservoir storage

Gauges	Statistics						
	(PBIAS)	NSE	R^2	RSR	r	d	VE
Srinagarind Dam	− 3.3	0.44	0.58	0.75	0.76	0.81	0.94
Vajiralongkorn Dam	0.6	0.77	0.78	0.47	0.88	0.94	0.91
Tha Thung Na Dam	− 0.2	0.54	0.68	0.68	0.82	0.9	0.99
Mae Klong Dam	− 0.2	0.9	0.9	0.32	0.95	0.97	1

Scenario 1: increased irrigation demand

In this scenario, the irrigation demand is assumed to increase by 15% keeping in view of the irrigation area and past data trends. It is found that for A2 scenario, the total unmet demand for agriculture is 28.4 MCM per year, for Tha Chin Basin is 0.18 MCM per year, and MWA is fully met. Under B2 scenario, the unmet demand for agriculture is 17.89 MCM per year and 0.18 MCM per year for the Tha Chin Basin. As compared to reference scenario, the reliability of water demands is decreased 0.52% for irrigation under A2 scenario. However, the reliability remains higher than 98%

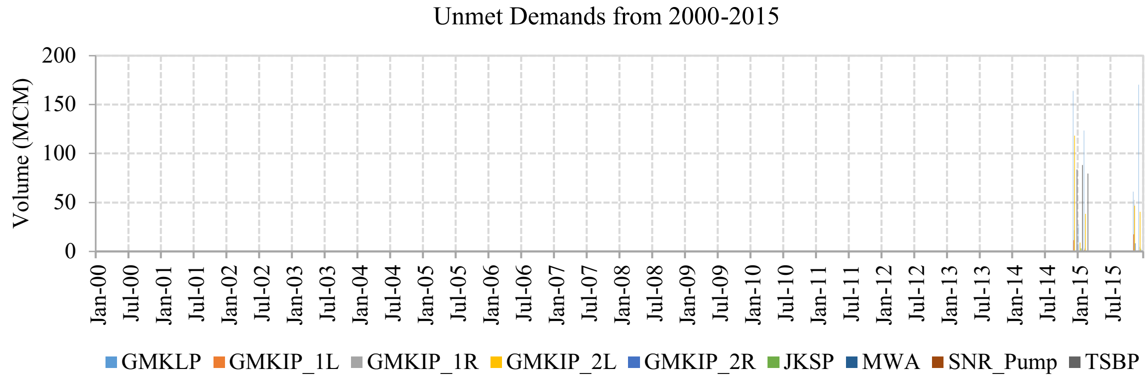


Fig. 14 Unmet water demands for the reference scenario

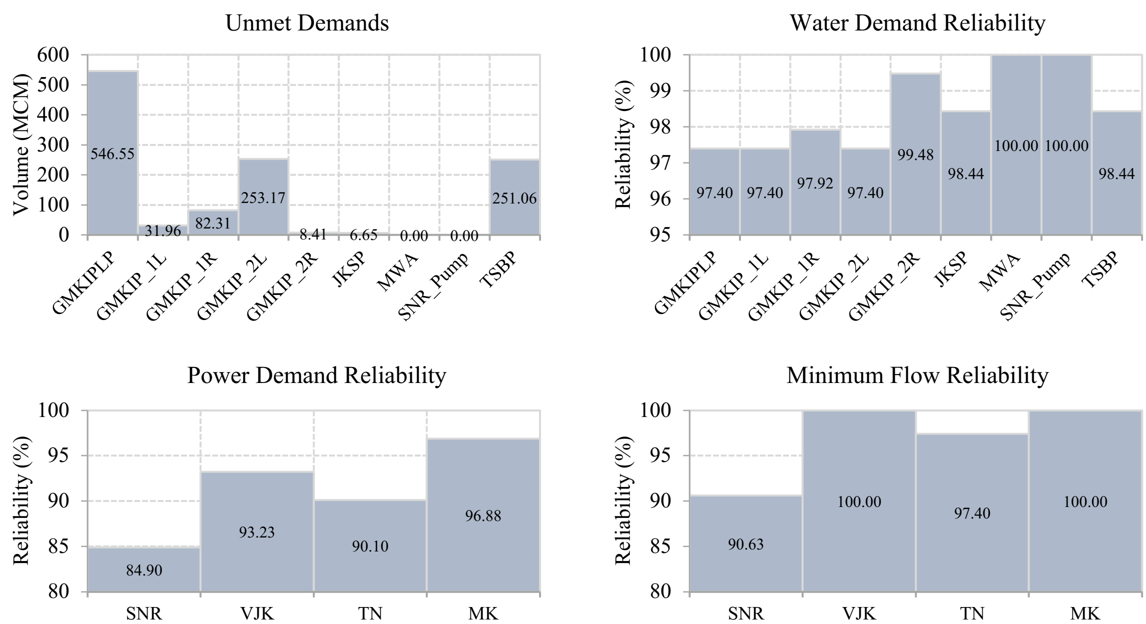


Fig. 15 Unmet water demands and reliability for water demands, hydropower and minimum streamflow for the reference scenario

for both scenarios which could be acceptable as an aspect of reservoir operation performance. Moreover, it will be possible if RID has projected to expand irrigation area in future.

Scenario 2: increased MWA demand

In this scenario, the discharge rate supplied to the Metropolitan Waterworks Association (MWA) is assumed to increase by 65% keeping in view its future demands for domestic water consumption. The results showed the slight increase in annual unmet demand for all the water use sectors. For A2 scenario, the annual unmet demand has become 17.25 MCM per year for agriculture, 0.18 MCM per year for the Tha Chin Basin, and is fully met for MWA demand. For B2 scenario, all the demands are fully met. Similarly, the reliability indices considered for all the water demand sectors are still reasonable as to bring this kind of projected scheme to carry out for a sustainable and successful practice in future.

Scenario 3: minimum flow at Mae Klong Dam

As the water conflicts have been facing among water users and involved stakeholders predominantly at the Lower Mae Klong Basin due to sea water intrusion, the scenario 3 is then proposed by increasing the minimum flow downstream of Mae Klong Dam from 50 CMS to 80 CMS. The results of this scenario showed that increasing discharge rate to fulfill the future instreamflow requirements may distinctly reduce the capability of allocating water for agricultural need and water transfer to adjoining area at some period of time.

Consequently, the annual unmet demand has increased into 9.96 MCM per year for agriculture, 0.18 MCM per year for the Tha Chin Basin under A2 scenario. The reliability for all the water demand sectors has also decreased. All the demands are fully met under B2 scenario. However, if RID cultivation plan of growing off-season crops during dry season will not be recommended to implement in some years in GMKIP, it will be possible to increase instreamflow rate downstream of Mae Klong Dam.

Scenario 4: increased Tha Chin Basin demand

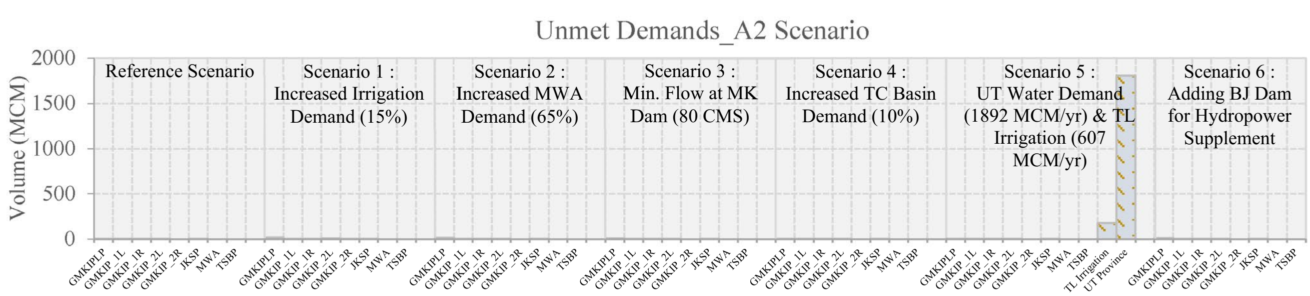
In this scenario, water diversion to neighboring Tha Chin Basin is increased by 10% of an existing demand. The annual unmet demand for agriculture is 5.97 MCM per year, and for the Tha Chin Basin it is 0.20 MCM per year. Meanwhile, the water demand for MWA is fully met under A2 scenario. All the demands are fully met under B2 scenario. It also expressed the satisfactory values of reliability for all the demand sectors which are more than 99% reliability for agriculture and minimum flow requirements and is still more than 95% reliability for hydropower generation for both scenarios.

Scenario 5: water supply to Uthai Thani Province and Tharo irrigation

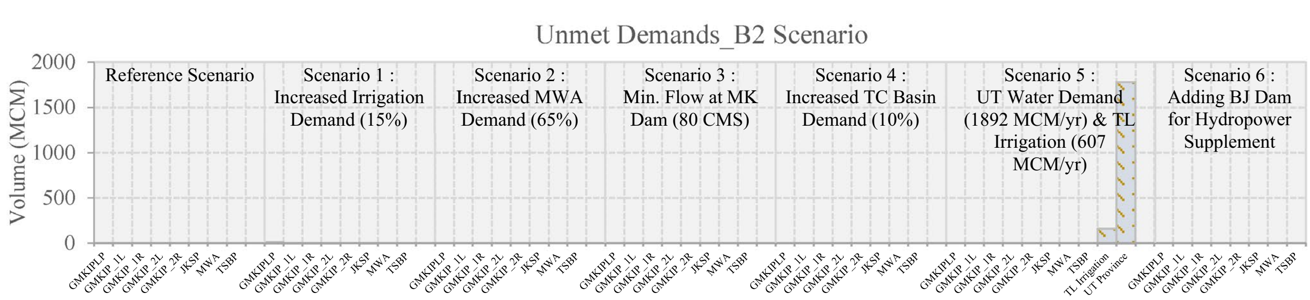
In this scenario, two new water demands are added. RID have recently planned to supply water to Uthai Thani Province from Srinangrind Dam at 1892 MCM per year and to Tharo Irrigation at 607 MCM per year from Mae Klong Dam. These demands were given less priority in terms of water supply in WEAP as compared to other demands. The simulated results showed the projected changes in average volume of unmet demand of 1.92 MCM per year for agriculture, 0.18 MCM per year for the Tha Chin Basin, 176.53 MCM per year for Tharo Irrigation, and 1806 MCM per year for water supply to Uthai Thani Province under A2 Scenario. The unmet demands are 162.72 MCM per year for the Tharo Irrigation and 1785 MCM per year for water supply to Uthai Thani Province, while all other demands are met under B2 Scenario.

Scenario 6: adding Ban Junday dam for Hydropower supplement

In this scenario, a re-regulated dam, Ban Junday Dam and hydropower plant with two generator units was considered 23.5 km downstream of Vajiralongkorn Dam as shown in Fig. 7. The hydropower demand is considered as 84.48 GWHr per year. The startup year for the dam operation is considered as 2020. The results expressed that increasing



(a)



(b)

Fig. 16 Unmet demands of all the scenarios under **a** Scenario A2, **b** Scenario B2

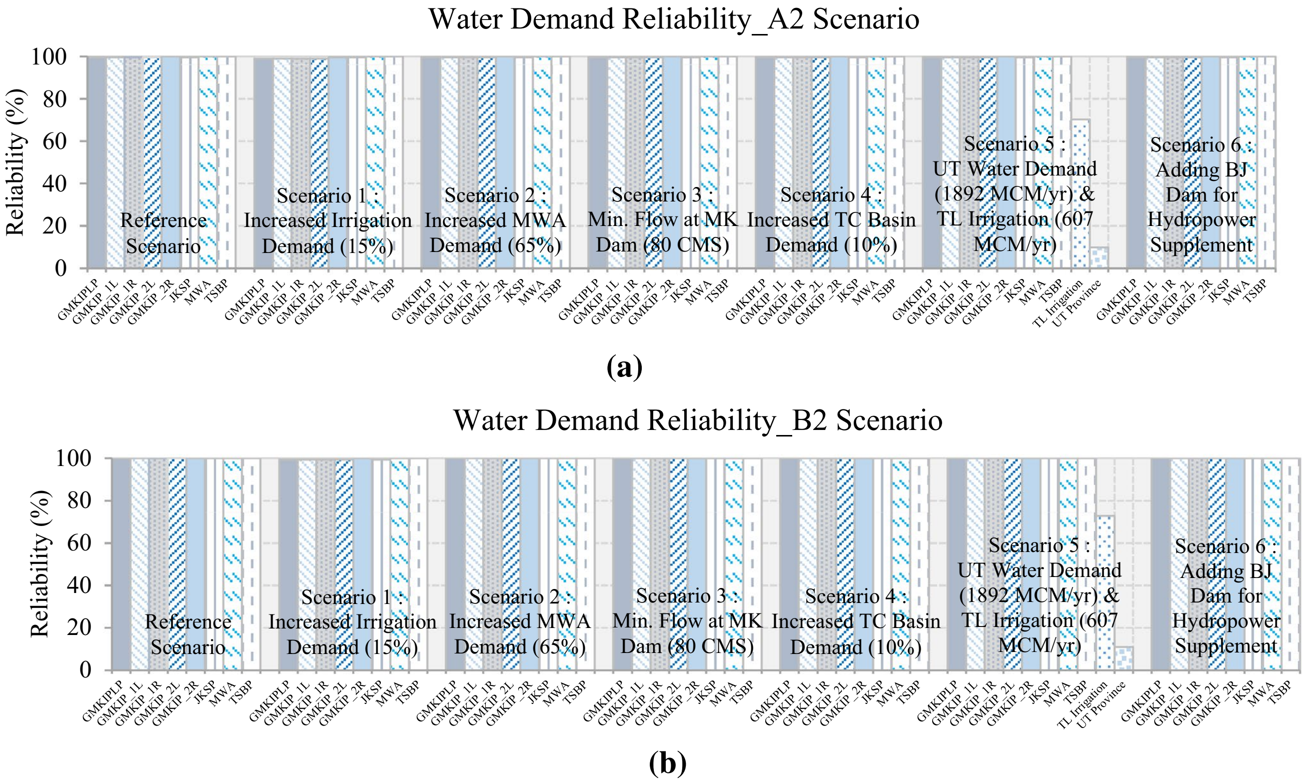


Fig. 17 Water demand reliability of all the scenarios under **a** Scenario A2, **b** Scenario B2

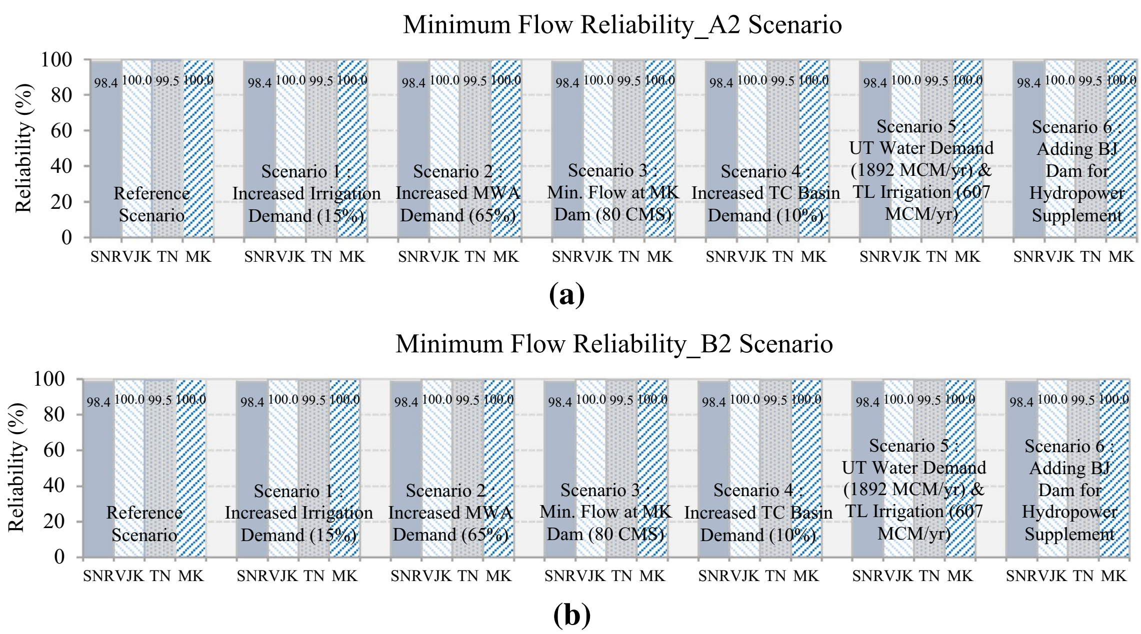


Fig. 18 Minimum flow reliability of all the scenarios **a** under A2, **b**under B2

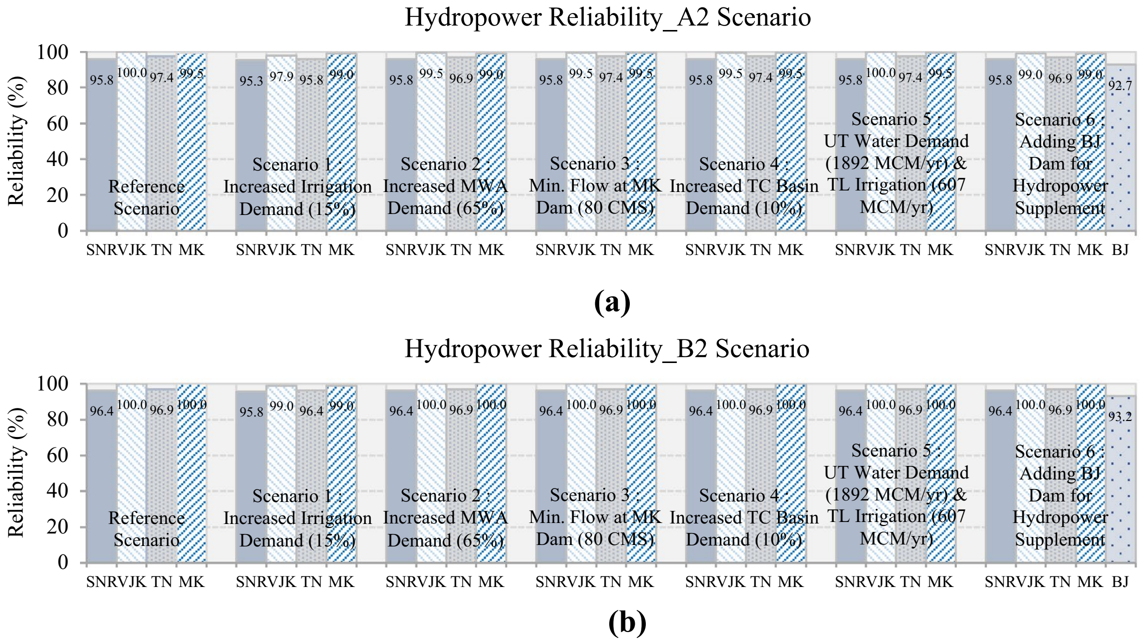


Fig. 19 Hydropower reliability of all the scenarios **a** under A2, **b** under B2

the power load has influenced on supplying water for agricultural demand. The volume of annual unmet demand for agriculture is 14.6 MCM per year and 0.18 MCM per year for diversion to the Tha Chin Basin under A2 scenario. But all the demands are fully met under B2 Scenario. The reliability of meeting hydropower demand from Ban Junday Dam is more than 92% for both the scenarios. The unmet hydropower demand has occurred in the first year of operation due to filling of the dam. This scenario has indicated that the project is feasible for meeting the increasing hydropower demand.

Conclusions

In this study, The Water Evaluation and Planning (WEAP) model was implemented for the Mae Klong Basin, Thailand, to assess the current situation of water resources and projected changes in water status in future by considering two SRES scenarios A2 and B2. The model results indicated that currently the basin has sufficient water to meet the water demands in the basin and out of basin. However, the basin is facing shortages in the dry season. Six scenarios were developed keeping in view of future plans for the basin by RID and EGAT, to evaluate the impact of increasing water demands on the water resources availability in the basin. Water shortages occurred in all scenarios indicating the need for better management policies to be adopted in the basin for long-term sustainability of water resources. Scenario five in which water is diverted from Srinagarind Dam to Uthai Thani Province and to Tharo Irrigation from the Mae Klong Dam has the most water shortages which suggests that through policy changes, the dams in the basin should be operated in such a manner to minimize the water shortage. It is recommended to fully utilize the use of groundwater resources in the basin to meet the increasing water demands through conjunctive water management. Scenario six in which a new hydropower project is considered downstream of Vajiralongkorn Dam is feasible and can help supplement the hydropower benefit. The implemented WEAP model for the Mae Klong Basin can be a useful tool for decision makers for effective management of water resources in the basin.

Limitations of the study

In this study, the rainfall-runoff modeling was done using simplified coefficient method based on data availability. The other methods, such as the soil moisture method and the MABIA method should be explored for more accurate modeling. Effects of climate change, which could have impacts on supply side of water availability in the basin, were referred to the previous study done by Shrestha in 2014. The water supply from groundwater resources is not considered in this study due to data constraints. However, effect of conjunctive use of surface and groundwater is considered in future research in the basin for better management of water resources to meet demands.

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