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Analysis of Hydrologic Variables Changes related to Large Scale Reservoir Operation by Using Mann-Kendall Statistical Tests in Thailand

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Abstract Recently, global warming has been significantly affected various hydrologic processes. The large scale multiple purposes reservoir is one of the countermeasures to manage and address both flood and drought problems. Therefore, an appropriate operation dam reservoir based on proper understanding of a change of hydrologic variable characteristics is important. This study applies the Mann-Kendall (MK) statistical trend test to analyze increasing, decreasing or trendless characteristics of precipitation, temperature, inflow to dam reservoirs, release from dam reservoirs, and storage volume in dam reservoir in Thailand from historical operation recorded data. The five large scale dam reservoirs located in the northern and central parts of Thailand are selected to analyze the trend of the Ping River basin (Bhumibol Dam), the Nan River basin (Sirikit Dam), the Pasak River basin (Pasak Jolasid Dam) and the Mae Klong River basin (Srinagarind and Vajiralongkorn dams). Those reservoir operation time series which consist of daily inflow, release, rainfall and temperature were analyzed and examined in association with various aspects of dam reservoir operations.

Keywords *Trend Analysis, Mann-Kendall trend test, Reservoir Operation, Thailand*

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Introduction

Climate changes cause clear temperature increase for decades or even longer periods (IPCC, 2013)[1)], which significantly affects various hydrologic processes of time and space distribution pattern and quantity in such as precipitation and evapotranspiration. There are numerous earlier studies which focus on trend analysis of atmospheric and hydrologic variables in quantity and quality using historical data and GCM data. For example, Tao *et al*.[2)] analyzed the trends of streamflow in the Tarim River basin during the past 50 years using historical data, and Duong *et al*.[3)] examined the impact of river discharge changes by using a distributed river flow routing model and GCM datasets in the Indochina Peninsula region.

In the Southeast Asian countries such as Thailand, agriculture is the main source of the economy as well as ensures the well-being of the people. Thus, to sustain the water resource into the future is quite essential. Unless the water resources are utilized with a balance approach of supply and demand, its sustainability will become at risk. Therefore proper planning of water resource development as well as the utilization based on uncertainty in climate change impact is very necessary. The large scale multiple purposes dam reservoirs are one of countermeasures to manage and address water resources problems. Therefore, the appropriate operation of dam reservoir based on a proper understanding of a change of hydrologic variables is very important.

In this study, the trend of various hydrologic variables related to dam reservoir operations such as inflow to dam reservoirs, release from dam reservoirs, dam storage as well as precipitation and temperature using long historical record are examined with the Mann-Kendall test. The trend analysis is one of the methods to support and confirm the change of hydrologic variables to propose an adaptive dam release operation rules and constraint in advance combining with GCM data analysis for the future.

Materials and Methods

The study area is Thailand which is located in the Southeast Asia with an area 513,115 km2. Its climate is tropical climate with clear dry and wet seasons. The seasons are defined as follow: the dry season starts from November until April and the wet season starts from May until October in the central and northern part of Thailand. In the western river basins dry season starts from January until June and wet season begins July until December.

Study areas and data collection

The five large scale dam reservoir basins located in the northern, western and central parts of Thailand as shown in **Fig. 1** are selected to analyze the historical trend of precipitation, temperature, dam inflow, dam release, and storage. The five basins are the Ping River basin with the Bhumibol Dam (BB), the Nan River basin with the Sirikit Dam (SK), the Pasak River basin with the Pasak Jolasid Dam (PS), and the Mae Klong River basin with the Srinagarind dam (SR) and Vajiralongkorn dam (VRK).

Daily temperature and precipitation data were collected from 25 meteorological stations for the period 1980-2011 and time series of monthly inflow, release and storage data were obtained from the Electricity Generating Authority of Thailand (EGAT) and Thai Royal Irrigation Department (RID) for the period of starting reservoir operation. The reservoir characteristics of reservoir description are given in **Table 1.** The spatial distribution of the selected meteorological stations in Thailand is shown in **Fig. 1**.

Table 1 Characteristic features of selected reservoirs

Name	BB	SK	SR	VRK	PS
Location	17°14′33″N 98°58′20″E	17°45′50″N 100°33′48″E	14°24′31″N 99°07′42″E	14°47′58″N 98°35′49″E	14°51′41″N 101°03′58″E
CatchmentArea (km2)	26,386	13,130	10,880	3,720	12,292
Max.Storage (MCM)	13,462	9,510	17,745	8,860	785
Mean Inflow (MCM)	5,783	5,780	4,790	5,585	2,725
Opening Year	1964	1974	1980	1984	1999
Period (years)	50	40	34	30	15

Trend analysis methods

Detecting trends in hydrologic, climatic, water quality and other natural time series has been an active topic for more than three decades now. Statistical tests for the detection of significant trends in hydrologic and climatologic time series can be classified as parametric and non-parametric methods. The parametric trend tests require sample data to be independent and normally distributed, while the non-parametric tests need only that the data be independant[4].

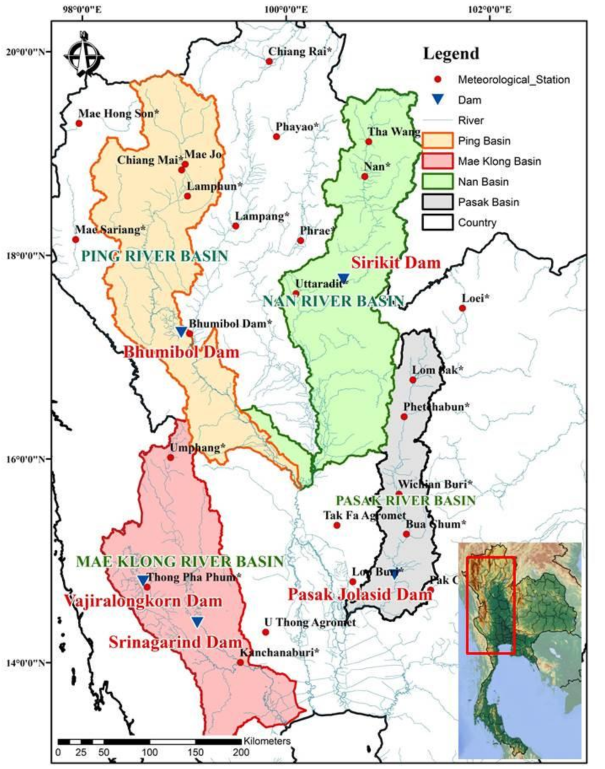

Fig. 1 Location map of large scale reservoirs and meteorological stations in Thailand

The Mann-Kendall trend test[4), 5)] is one of the widely used non-parametric tests to detect significant trends in time series. The Mann-Kendall trend test is based on the correlation between the ranks of a time series and their time order. For the statistics *S* is calculated as equation (1). This statistic represents the number of positive differences minus the number of negative differences for all the differences considered as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \quad (1)$$

where n is the number of total data points, x_i and x_j are the data values in time series i and j ($j>i$), respectively, and sgn (x_j-x_i) is the sign function as:

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} +1, & if \;\; x_j - x_i > 0 \\ 0 & if \;\; x_j - x_i = 0 \\ -1 & if \;\; x_j - x_i < 0 \end{cases} \quad (2)$$

The variance of Mann-Kendall statistic is calculated by equation (3) as

$$Var\,(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

where n is the number of total data points, m is the number of tied groups. The tied group mean a simple data having a same value. The t_i indicates the number of ties of extent i. In case of the sample size $n > 10$, the standard normal test statistic Z_S is estimated by equation (4) as

$$Z_S = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, if\ S>0 \\ 0\ \ if\ S=0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, if\ S<0 \end{cases} \qquad (4)$$

The positive values of Z_S show increasing trends while negative Z_S values present decreasing trends. In this study 1% and 5 % significance level (α) were used. When $|Z_S| > Z_{1-\alpha/2}$, the null hypothesis is rejected and significant trend exists in the time series. $Z_{1-\alpha/2}$ is obtained from the standard normal distribution table. Therefore, the null hypothesis of no trend is rejected if $|Z_S|$> 1.96 and $|Z_S|$ > 2.576 at the 5% and 1 % significance level respectively.

Data analysis

The observation data used in this study consists of a daily observation of precipitation, temperature, daily inflow, release and volume storage. The daily precipitation, dam inflow and dam release flow data were summed up for monthly, seasonally, and yearly and developed monthly, seasonally and annual time series data for the trend analysis. The daily temperature data were averaged monthly, seasonally, and yearly and developed for each time series data. Similarly the dam storage volume time series were averaged on each month. After compiling all-time series data on each parameter, the monthly time series in the designed month was selected to generate new time series for the Mann-Kendall trend analysis.

In addition, the seasonal analysis also calculate by dividing on dry season (November to April) and wet season (May to October) for the northern and central of study area. The climate for western of study area is delayed, so the calculation was chosen the dry season (January to June) and the wet season (July to December) based on each climate characteristics.

Results and discussion

Analysis of temperature and precipitation trend

Results of applying statistical tests for seasonal and annual temperature and precipitation trend over the period 1980-2011 are presented in **Table 2** and **Fig. 2**. In **Table 2**, the Z_S values in equation (4) are presented. The positive values represent the increasing trend and the bold values shows statistically significant at the 5% or 1% significant level.

All of the entire stations show the little significant increasing trends except some stations near to the BB dam stations while the other stations trends present increasing trend in term of temperature and rainfall. For the results of temperature trend, the Wichianburi and Maejo stations in the Pasak River basin and the Ping River basin showed dramatically insignificant increasing trends at the 1% significance level of temperature in all season. The other stations have slightly increasing and decreasing trends in dry and wet seasons. The temperature in the Pasak, Nan and Mae Klong River basins shows the increasing trends, which means the evapotranspiration trend in those river basins would increase because the temperature is a main factor of evapotranspiration components.

Table 2 Results of the statistical tests for seasonal and annual temperature and precipitation over the period 1980-2011

Station	Temperature			Precipitation		
	Dry Season	Wet Season	Annual	Dry Season	Wet Season	Annual
Bhumibol Dam	0.214	-0.714	-0.018	0.712	-0.188	-0.021
Chiang Mai	0.464	**-2.194***	-1.053	-0.335	-0.314	-0.649
Chiang Rai	**1.963***	0.839	1.731	0.251	-0.565	-0.523
Lampang	**2.569****	0.036	1.855	0.126	-0.628	-0.607
Lamphun	0.788	-1.632	-0.263	-0.068	1.564	1.19
Mae Hong Son	-0.244	-0.732	-0.619	0.555	0.795	0.795
Mae Jo	**2.963****	0.691	**2.904****	0.34	-1.216	-1.112
Phayao	-0.338	0.319	0.638	-0.187	**2.108***	1.836
Mae Sariang	0.143	-1.07	-0.749	1.13	0	0.251
Nan	1.035	0.125	0.517	0.272	0.188	0.293
Phrae	-0.393	-0.624	-0.232	1.193	0.649	0.733
Tha Wang Pha	-0.892	1.035	0.91	0.054	0.715	0.412
Uttaradit	1.427	-0.125	0.5	0	-1.047	-1.214
Phetchabun	1.285	0.178	1.285	**2.156***	0.9	1.465
Pak Chong	**2.623****	-0.963	1.267	0.921	**2.219****	**2.623****
Lom Sak	**2.177***	-0.125	1.409	0.076	0.195	0.433
Lop buri	0.178	0.071	0.107	0.23	-1.088	-0.481
Loei	1.249	-0.624	0.892	0.586	1.005	1.235
Bua Chum	0.393	0.225	0.161	-0.303	0.195	-0.206
Wichian Buri	**2.814****	**2.176***	**2.701****	1.741	0.108	0.966
Tak Fa	0.696	-0.731	0.232	0.954	1.047	1.17
Kanchanaburi	-0.892	1.873	0.232	-0.147	-0.586	-0.356
Thong Pha Phum	0.731	**2.301***	1.855	0.52	0.011	0.412
Uthong	-1.82	0.464	-0.892	**-3.181****	**2.972****	-0.544
Umphang	0.535	-1.356	-0.393	1.363	0.824	1.761

Bold Character represent trends identified with
*Statistically significant trends at 5% significance level (1.960)
**Statistically significant trends at 1% significance level (2.576)

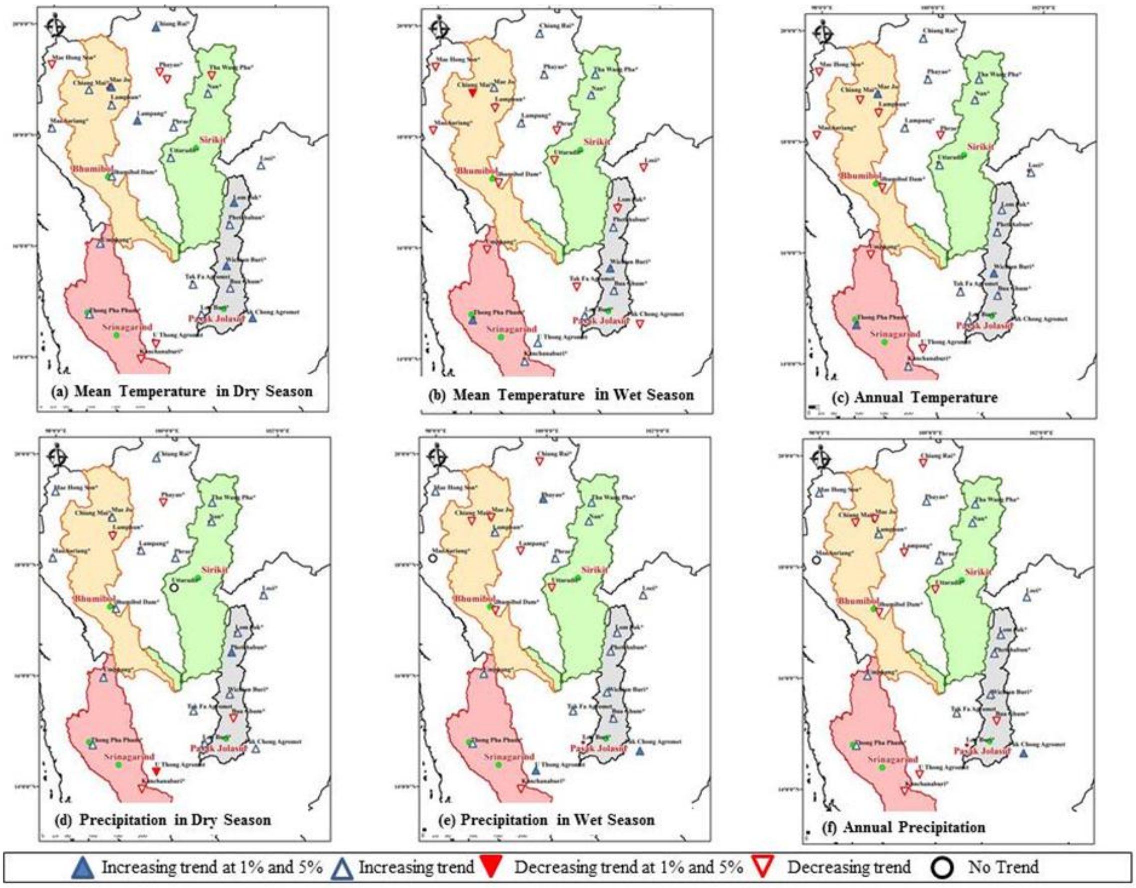

Fig.2 Spatial distribution of meteorological stations with increasing, decreasing and no trends for seasonal and annual data during the period 1980-2011.

According to the precipitation trend results, the precipitation trends of the Pasak, Nan and Mae Klong River basins also slightly increase as similar trends with the temperature.

Analysis of inflow trend

The output of the analyzed inflow series was summarized in **Table3**. The inflow series of the SK dam at the Nan River basin and the SR dam at the Mae Klong River basin were found significant increasing trends throughout the year, which are corresponding with the increasing precipitation trends. Both increasing and decreasing trends were detected at the BB, PS and VRK dams. The VRK and BB dam have a strong significant decreasing trend at 1% significance levels in early dry season. The Pasak reservoir was found only three months of slightly increasing trends comparing with other nine month significant decreasing trends, even though, the precipitation trends in the Pasak River basin have been detected increasing trends in all stations that cover the basin. This suggests the higher evapotranspiration rate occurred, which made the reducing the amount of water resources in the basin.

Table 3 Results of the statistical tests for monthly, seasonal and annual inflow over the period from the operation to 2013

Month/Season	Test statistic (Zs)				
	BB	SK	PS	SR	VRK
Jan	**-2.141***	1.27	0	0.415	**-2.12***
Feb	-1.824	**2.552***	-1.204	0.978	**-2.345***
Mar	-0.351	0.804	-0.985	1.038	-0.769
Apr	-0.97	0.781	0.109	0.326	**-2.157***
May	1.029	0.874	-0.495	0.83	0.732
Jun	0.151	0.408	-0.594	0.86	0.071
Jul	0.46	0.92	-1.188	**1.986***	**2.212***
Aug	-0.067	0.804	-0.891	**2.194***	1.249
Sep	-0.033	1.014	0.495	1.393	1.855
Oct	0.184	0.478	0.891	1.127	0.928
Nov	-1.422	0.384	-1.188	0.296	0.036
Dec	**-2.894****	**2.598****	**-2.078***	0.385	0
Dry Season	-1.939	1.766	-1.642	1.334	0.319
Rainy Season	0.151	0.851	0.396	1.186	**2.07***
Annual	-0.233	0.702	0.495	1.512	**1.97***

Bold Character represent trends identified with
*Statistically significant trends at 5% significance level (1.960)
**Statistically significant trends at 1% significance level (2.576)

Analysis of release flow trend

The monthly, seasonal and annual trends of release flow obtained by the Mann-Kendall test are given in **Table 4**. According to these results, the significant increasing trend at 1% significance level of release flow during dry season were found except the Pasak dam, however the release flow of the Pasak dam has a little significance increasing trends especially on December and January at the 1% significance level. The inflow trends of the BB and SK dams during early wet season (May to July) found increasing trends as shown in **Table 3**. Therefore, the release of the BB, SK and PS dams in wet season have significant decreasing trend to store the flood flows in the Ping, Nan and Pasak Rivers. In brief, the results found generally increasing significant trends in dry season of release flow in all reservoirs for high water demand, and decrease trends in the BB, SK, and PS dams to store water in the rainy season.

Table 4 Results of the statistical tests for monthly, seasonal and annual release flow over the period starting from the operation to 2013

Month/Season	Test statistic (Zs)				
	BB	SK	PS	SR	VRK
Jan	**3.543****	**4.928****	**3.266****	**3.579****	**2.72****
Feb	**4.215****	**3.944****	1.683	**4.092****	**4.858****
Mar	**2.595****	**2.179***	1.584	**3.765****	**3.395****
Apr	1.457	0.478	-0.792	**2.846****	**4.221****
May	-1.405	-0.711	0	**3.172****	**2.532***
Jun	-1.69	-0.151	0	2.046*	-0.469
Jul	**-2.476***	-1.456	-0.693	**2.075***	0.206
Aug	**-2.108***	-1.34	-0.693	1.66	1.069
Sep	**-3.279****	**-2.039***	-0.792	0.049	-0.019
Oct	-2.509*	-1.2	0.891	**3.143****	1.427
Nov	-0.569	-0.198	-0.891	**2.787***	**2.676****
Dec	1.941	**3.111****	**2.771****	**3.41****	**2.034***
Dry Season	**2.957****	**3.29****	0.766	**3****	**3.358****
Rainy Season	**-2.225***	-1.13	0.099	1.832	1.356
Annual	0.353	1.379	0.396	**3.13****	**2.72****

Bold Character represent trends identified with
*Statistically significant trends at 5% significance level (1.960)
**Statistically significant trends at 1% significance level (2.576)

Analysis of storage trend

Results of the Mann-Kendall test to the monthly storage volume at the end of each month are presented in Table 5. As shown, the majority of the monthly trends in the BB and PS dam have a significant decreasing trend due to reservoir operation based on existing rule curve while the SR dam shows increasing trend throughout the year. The SK and VRK dams remain the similar trends of increasing trends in wet season and of decreasing trends in dry season as a natural condition. Moreover, the significant decreasing trend at the 1% significance level from February to July of BB Dam and from January to April and August of PS dam were detected.

Insufficient and excess storage volume

Insufficient and excess storage volume below or exceeding the rule curves of all reservoirs were also evaluated from the beginning of each dam operation. The insufficient storage volume means the amount of volume below the lower rule curve while the excess volume represents the total of volume exceeding the upper rule curve. The explanation of insufficient and excess storage volume is illustrated as **Fig. 3.** The results of this analysis are summarized in Table 6. At the BB dam, increasing of insufficient storage volume trends was detected, which is corresponding on previous analysis of reduced inflow and increasing outflow trends results. The PS Dam also had a similar significant inflow and outflow trends results with the BB dam nevertheless the results of insufficient and excess storage volume results of the PS dam have indistinct. The SK, SR and VRK dams show gradually a rising trends of excess storage volume same an inflow trends of preceding section that represent the water resources in those areas would be increased.

Table 5 Results of the statistical tests for monthly, seasonal and annual storage over the period starting from the operation to 2013

Month	Test statistic (Zs)				
	BB	SK	PS	SR	VRK
Jan	-1.491	-0.012	**-1.971***	1.186	1.294
Feb	**-2.112***	-0.827	**-2.847****	1.127	0.807
Mar	**-2.629****	-1.456	**-2.956****	0.889	0.619
Apr	**-2.801****	-1.619	**-3.175****	0.741	-0.169
May	**-2.681****	-1.503	-1.534	0.415	-0.694
Jun	**-2.422***	-1.107	-1.782	0.682	-0.178
Jul	**-1.982***	-0.641	-1.881	0.652	0.107
Aug	-1.664	0.128	**-2.573****	1.275	1.534
Sep	-1.577	0.454	-1.089	1.571	1.249
Oct	-1.284	0.618	1.386	1.601	1.463
Nov	-0.957	0.757	1.089	1.423	1.427
Dec	-1.112	0.734	-0.693	1.156	1.463

Bold Character represent trends identified with
*Statistically significant trends at 5% significance level (1.960)
**Statistically significant trends at 1% significance level (2.576)

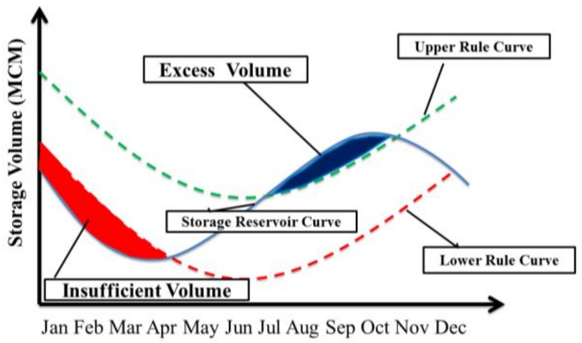

Fig. 3 Explanation of insufficient and excess storage volume

The number of insufficient events in the BB, SK and SR reservoir were found biennially on average. The PS dam has a small capacity comparing with other dams, so many insufficient and excess events detected within fifteen years. However, the VRK dam is also found the excess events with fourteen times to cope with flood. According to the dam characteristics in **Table.1**, the large scale reservoir such as the BB and SR dams have an advantage to address the flood for four and two events, respectively.

Table 6 Results of insufficient and excess storage volume.

Dam		Number of Event	Zs	
BB	Insufficient	24	1.15	Increasing
	Excess	4	-	-
SK	Insufficient	28	-0.01	Decreasing
	Excess	14	0.99	Increasing
PS	Insufficient	10	0.00	No Trend
	Excess	17	0.72	Increasing
SR	Insufficient	17	-0.03	Decreasing
	Excess	2	-	-
VRK	Insufficient	8	-1.86	Decreasing
	Excess	14	0.00	No Trend

Conclusions

The trends of precipitation, temperature, dam inflow, and dam release flow and volume storage were analyzed statistically based on long term historical data by using the Mann-Kendall trend test. Our findings are summarized as follows:

- Through the analysis, we found that the temperature and precipitation trends were increasing trends nevertheless Ping River basin temperature and precipitation trends were decreasing trends.
- The water resources availability in term of inflow to BB dam and PS Dam were decreasing trend during dry season. The inflow of all reservoirs in rainy season has increasing trends.
- For dam release from the reservoirs, generally increasing significant trends in dry season of release flow in all reservoirs. Only BB and SK dam has decreasing trends during rainy season.
- As a result, dam storage for BB dam found dramatically decreasing trends throughout the year while the SR dam detected decreasing trends.
- These insufficient and excess storage results indicate the increasing trends of water shortage in BB dam (Ping River basin) and PS dam (Pasak River basin) and also raising the trend of flood in SK dam (Nan River Basin) and both dams in Mae Klong River Basin.

We showed the climate change impacts have been already appeared in water resources in Thailand. The further study will be combined with the analysis of the historical data and GCM outputs. The analysis using a hydrologic model and GCM outputs are ongoing to predict future dam inflow under a changing climate to develop a new rule curve for adaptive dam reservoir operation.

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