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Hydrological drought frequency analysis of the Yom River, Thailand

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Abstract

The Yom River is subjected to flooding and drought for six months each year. Several studies suggested storing water during the rainy season for use in the dry season. None of them, however, quantified the precise amounts of storage needed along the river with acceptable risks. In an attempt to quantify the required storage, we performed frequency analyses to learn the severity of streamflow droughts along the river. A deficit volume, defined as when the amount of flow is less than a selected threshold level, was used to characterize a drought event. The Weibull distribution model was chosen for analysis after comparison of log normal and Pareto models with an empirical distribution. Results showed a more severe drought condition exists towards the downstream section of the river where paddy fields are larger. A large deep groundwater irrigation project located near the mid-section of the river mitigates drought along this section. Drought is more severe further downstream from the project. One reason for this is that the baseflow is cut off by groundwater abstraction. This method presented can help to quantify the severity of hydrological drought along any river so that drought management measures can be undertaken.

Keywords: Hydrological drought, Frequency analysis**,** Deficit volume, Weibull distribution, Yom River

1. Introduction

Typical climatic condition of Thailand is the semiannual wet and dry seasons. According to Koppen climate classification system, it is a Savanna, wet-dry tropical climate (Aw). Most of the rainfall occurs between May and October and the rest of the year is dry. Water scarcity or drought is a typical phenomenon for all Thai rivers at varying degree of severity in both space and time, especially at the end of the dry season. Drought in the Yom River is more pronounced than others for its lack of large dams and reservoirs. This natural flow system, in turn offers beneficial information for hydrological studies.

Drought is one of the most dangerous natural hazards. While its effects is slow to build, its impacts cause extensive damage [1]. In 2015, Thailand was affected by severe drought almost everywhere which affected its economy extensively. Irrigation for the second paddy rice season was not allowed. Many places experienced a shortfall in water supply. Reserves in the majority of the large dams were below average capacities at the end of wet season. Drought can impacts community water supply, irrigation, industry, and environment [2-3].

Generally, there are 4 kinds of drought, namely meteorological, agricultural, hydrological, and social and economical drought [4]. Meteorological drought occurs when precipitation is below normal for an extended period of time. Reduction in rainfall depletes soil moisture which affect crop consumptive uses resulting in an agricultural drought. Reduction in rainfall and soil moisture in turn decreases river flow and groundwater storage causing a hydrological drought. These drought processes generate social and economic chaos where communities, farmers, industries, stream ecologies, etc. fight for their share of water leading to what is called a social and economic drought [5]. Hydrological drought is of our interest because it is the most common to affect our activities and the easiest to be manipulated.

Drought can be defined as naturally and abnormally low water availability at a specific location for an extended period of time and affecting living standards [2]. Hydrological drought can be defined is the river flow or groundwater storage being less than a specified value. Providing the complexity of the Yom Basin groundwater flow, this study focused on the Yom River streamflow drought only. The river and the groundwater basin are related by base flow [6].

Additionally, streamflow drought is the least difficult to alleviate with proper water management [7]. The most common approach is to store surplus water for use in the time of deficit or to convey water from the plenty to the scarce [8]. A few researchers have studied how to cope with hydrological drought of the Yom River but none considered its drought characteristics e.g. [6],[9-10]. Drought characterization and frequency analysis are needed to make informed decisions and for sizing of storage and conveyance channels. Therefore, the main objective of this study is to determine the severity of streamflow drought along the main course of the Yom River at a specified probability or return period.

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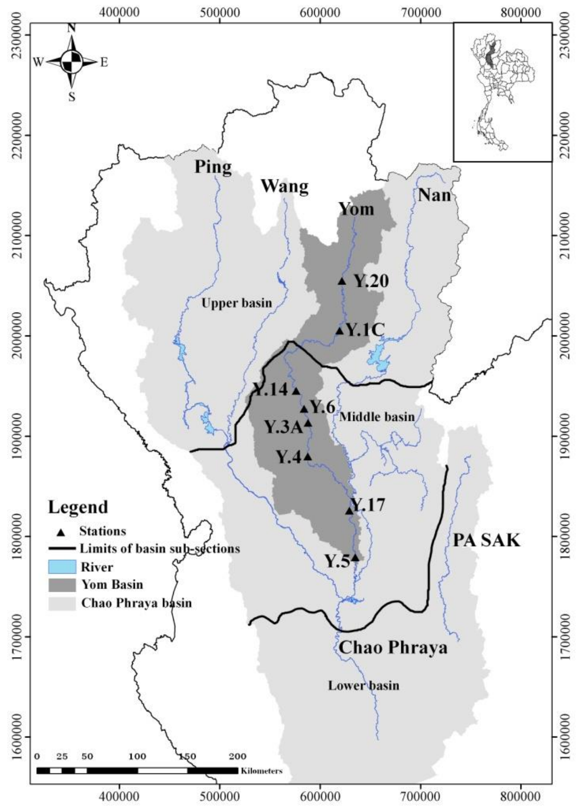

Figure 1 Chao Phraya Basin with Yom River as one of the main tributaries

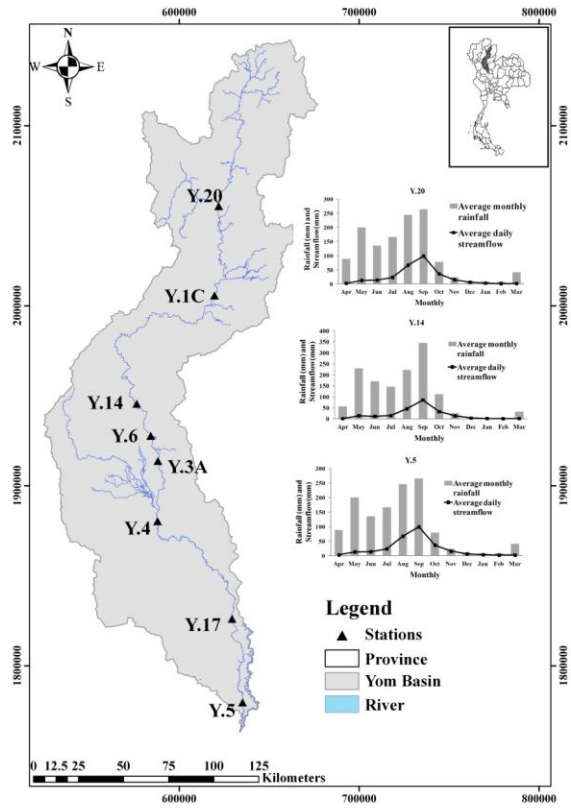

Figure 2 Hyetographs and hydrographs along the Yom River

Section 2 of this paper describes the Yom River and its environments. The theory of hydrological drought characteristics is presented in Section 3 by emphasizing the deficit volume. Section 4 illustrates several theoretical distribution functions together with the empirical probability distribution of Weibull. The methodology of frequency analysis is explained in Section 5 and the results and discussions are in Section 6. Finally, main findings are concluded in Section 7.

2. The Yom River

The Yom River is one of several main tributaries of the great Chao Phrya River. The Yom watershed is a subwatershed of the Chao Phraya Basin (Figure 1). The Chao Phraya Basin is divided into 3 parts, the upper, middle, and the lower part [11]. The division between the upper and the middle is at about the boundary between Phrae and Sukhothai provinces, the upper part is mountainous while the middle is flat plain. The division between the middle and the lower part is between Nakhon Sawan and Chainat Provinces. The lower part is a low lining area of large fertile paddy fields. The Yom River occupies the upper and middle parts together with the Ping, Wang, and Nan Rivers while the Pasak and Sakagrung Rivers in the lower part.

The Yom originates from the Pi Pun Nam mountain range which is the watershed divides between the Yom and the other three rivers, the Wang, the Nan, and the Mekong on the West, East, and North, respectively. All four tributaries, the Ping, Wang Yom, and Nan, flow from Northern part of Thailand parallel with each other to the Central. The Yom merges into the Nan River at Chumsaeng, Nakhon Sawan Province then meets with the Ping at Pak Nam Po, Nakhon Sawan Province, to form the Chao Phraya River. The length of the Yom is 735 km. with elevations from 300 m. at the river head to about 20 m. above mean sea level at the outlet. Its watershed covers 25,180 km^2 between longitude 99˚ 13ʹ – 100˚ 5ʹ E and latitude 15˚51ʹ – 19˚ 24ʹ N [11]. Average monthly rainfall shows a bimodal pattern in the wet season from April to October. The two peaks are in May for minor and August for major peak. The average annual rainfall of the whole watershed is 1,113 mm, with the upper part having slightly higher rainfall than the lower. Surface flow follows rainfall pattern with one peak in September (Figure 2). Petchprayoon et al. [12] studied the change of land use of the Yom watershed from 1990 to 2006 and found very small changes from forest to urban. In 2006, the watershed comprises 46.2% forest, 51.5% agriculture, 1.9% urban, and 0.3% water body.

Eight gauging stations were chosen along the river for this study, listing from upstream are Y.20, Y.1C, Y.14, Y.6, Y.3A, Y.4, Y.17, and Y.5 (Figure 2). Their specified locations, elevations, and watershed areas are shown in Table 1. The data of average daily streamflow for 15 water years from 1998 to 2012 were used in this study except stations Y.4 and Y.5 which were 8 and 7 water years, from 1990 to 1997 and from 1991 to 1997, respectively. The water year for Thailand goes from April to March. It is practical to use water year, instead of calendar year, in hydrological drought analysis to avoid separation of the events from the same water year.

3. Deficit volume

Streamflow drought is usually characterized by *deficit volume* and *deficit duration*. These two variables are actually related to one another in nonlinear manners [13-16]. Since the deficit volume accumulates during the drought going on therefore duration could be a function of deficit volume.

Table 1 Locations, elevations, and watershed areas of gauging stations

Stations	**Locations**	**UTM**		**Elevations**	**Areas**
		Easting	**Northing**	**(m, amsl.)**	**(km²)**
Y.20	Song, Phrae	621110 E	2056660 N	212	5,410
Y.1C	Muang, Phrae	618960 E	2005355 N	157	7,624
Y.14	Sri Suchnalai, Sukhothai	575916 E	1945575 N	70	12,131
Y.6	Sri Suchnalai, Sukhothai	583720 E	1927911 N	69	12,658
Y.3A	Swankalok, Sukhothai	588403 E	1915402 N	62	13,583
Y.4	Muang, Sukhothai	588810 E	1878694 N	53	17,731
Y.17	Samngam, Pichit	629414 E	1827400 N	40	21,415
Y.5	Po Thale, Pichit	634735 E	1779836 N	34	22,344

Among the two, only the deficit volume is preferable in drought mitigation analysis such as for storage design and operation. Therefore, we are focusing on how to analyze and predict streamflow deficit volume in this study.

Streamflow drought happens when the discharge being lower than a specified value (threshold level) which can be fixed or varied with time [17], as in Figure 3 for a fixed value. Yevjevich [18] initiated the *theory of run* to be used with streamflow drought analysis. It is now known as threshold level method. The volume of flow during the time of streamflow being lower than a specified value is a deficit volume. Large deficit volume identifies severe drought event which needs a reasonable large storage for coping with the drought. Series of deficit volume data can be obtained from a series of daily discharge of streamflow at a gauging station. In this study we used the daily discharge data from the aforementioned eight stations (Figure 2). Threshold level is a subjective value, it might have been estimated from total water demand [17], from percentage of average streamflow [19], and from flow duration curve [20].

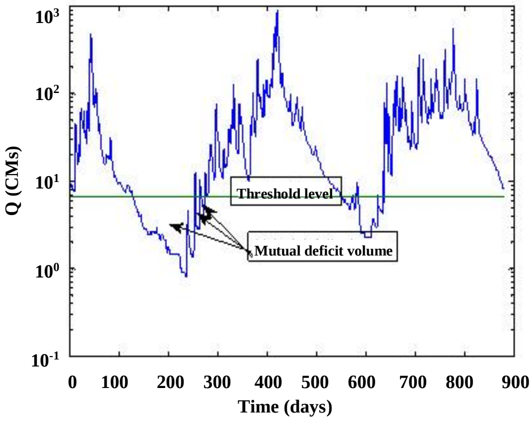

Figure 3 Example of deficit volumes of Y.20 with a fixed threshold level

Several researchers prefer to determine a threshold level value from percentile of the flow duration curve of the site [20-22]. We also follow their suggestion. A flow duration curve illustrates the percentage of time a given streamflow was equaled or exceeded during a specified period of time [23]. It can be constructed from the period-of-record data or annual-based [24-25], and we used the first kind in this study. An example of the flow duration curve of station Y.20 from the record data during 1988-2012 is shown in Figure 4 which also showing the discharge at 70 percentile (Q_{70}) of 6.2 m^3/s. Whenever discharge of Y.20 is less than 6.2 m^3/s then the drought of Y.20 prevails.

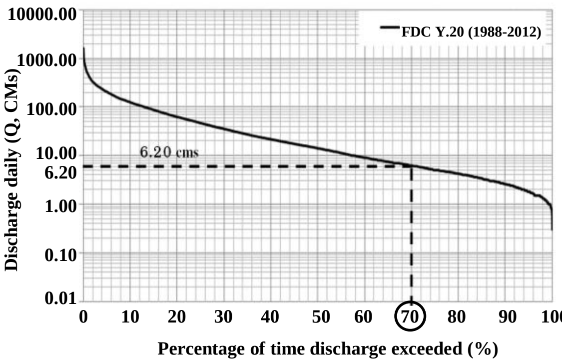

Figure 4 Flow duration curve of Y.20 from 1988 to 2012 data

The deficit volume equals to the volume of flow minus the threshold level, by considering only positive value. In the form of equation can be written as:

$$D_{t+\Delta t} = D_t - (Q_{t+\Delta t} - Q_o)\,\Delta t \quad \text{if } D_t - (Q_{t+\Delta t} - Q_o)\,\Delta t > 0 \qquad (1)$$

$$D_{t+\Delta t} = 0 \quad \text{if } D_t - (Q_{t+\Delta t} - Q_o)\,\Delta t \leq 0 \qquad (2)$$

$$D_m = \max(D_{t+\Delta t}) \qquad (3)$$

where $D_{t+\Delta t}$ and D_t are deficit volumes at times t+Δt and t respectively; $Q_{t+\Delta t}$ is streamflow discharge at time t+Δt, and Q_0 is threshold level. The Δt is 1 day for this study. Eq. (2) implies deficit volume to be positive. The maximum value of evaluated volumes is the representative deficit volume (D_m) of that event. Since both the average daily streamflow Q_t and the threshold level Q_0 are random in nature therefore the deficit volume D_m is also a random variable. Random variables must be treated as independent and identically distributed (iid) data [26]. To avoid mutually dependent drought event, we must pool several mutual events into one event. Three pooling procedures have been scrutinized and compared by Fleigh et al. [27] i.e. inter-event time method [28], moving average procedure [21], and sequential peak algorithm [29]. They found the three pooling procedures are compatible, however, they prefer the moving average procedure [27]. Our preference is the sequential peak algorithm in this study because it is appropriate for design and operation of water resource storage and conveyance which is important for drought circumvent [30]. To apply the sequential peak algorithm for pooling mutually dependent drought event is by following the aforementioned method in Eqs. (1-3). The definitions of deficit volume and duration obtained from sequential peak algorithm are illustrated in Figure 5.

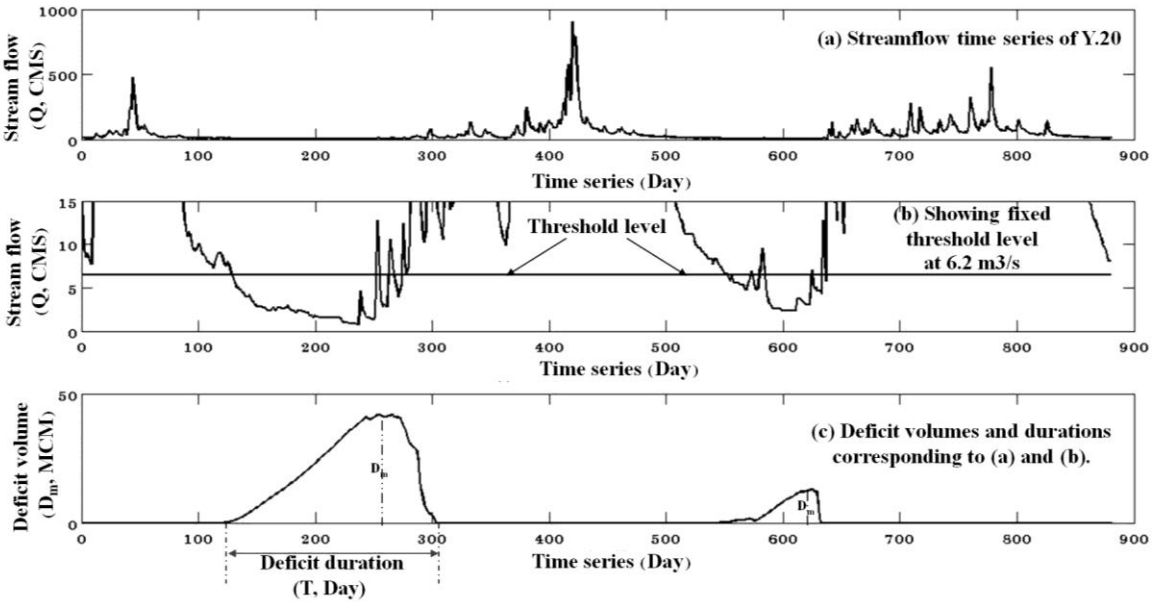

Figure 5 Sequential peak algorithm to overcome mutual drought events; (a) streamflow time series of Y.20, (b) showing fixed threshold level at 6.2 m^3/s, and (c) deficit volumes and durations corresponding to (a) and (b).

4. Frequency analysis

Frequency analysis is a statistical method used to estimate the average recurrence frequency of an hydrological event [23],[26],[31]. The drought events in the Yom River are assumed to follow a theoretical probability distribution. The population probability characteristics of the Yom's drought events were estimated from samples drawn from the droughts during 1988 to 2012. Several theoretical distributions of the drought samples were compared to the empirical probability distribution. The best matched theoretical distribution was chosen for drought estimations.

We always treat a hydrological event in annual manner. For example, a 10-year drought means this drought severity or higher will recur every 10 years on average. In other words, it can happen in any year at the probability of 0.1. In terms of *return period*, the above mentioned event has a 10-year return period. Therefore the events are sampled only one sample each year, which is called *maximum annual series* (mas). In case of hydrological drought, it can occur several events in a year e.g. drought events in this study happen on average of 1.77 events annually. When all drought events are used for probability distribution estimation, they are called *partial duration series* (pds). We use *cumulative probability distribution function* (cdf) to obtain the frequency of occurrence, which can be written as,

$$F(x) = Pr(X<=x) \quad (4)$$

where F is non-exceedence probability, X is random variable e.g. deficit volume, x is a real number, and Pr is probability. Eq. (4) indicates probability of X is less than or equal to x. For exceedence probability G(x), we have,

$$G(x) = Pr(X>x) = 1 - F(x) \quad (5)$$

which G(x) is probability of random variable X being higher than x. Empirical exceedence probability $G_m(x)$ of Weibull model can be calculated by listing deficit volume data from highest to lowest values then the corresponding $G_m(x)$ is

$$G_m(x) = m/(n-1) \quad (6)$$

where m is the ranking of orderly data, and n is total data number.

Theoretical cdf can be chosen from many models. One of the most popular model is the log-normal distribution. However, the generalized Pareto model is popular for dealing with partial duration series [32]. And for drought analysis, the theoretical Weibull distribution model is supposed to be one of the best [33]. Therefore in this study, we compared these three theoretical models to the empirical model and the best of these three is to be used for further analyses. The 2-parameter models are accepted in this study because each data set does not reach 30 samples which is suitable for 3-parameter models [34-35]. These models can be expressed in the forms of equations as following. Log-normal distribution equation is of the form [2],

$$F(x) = \Phi((\ln(x) - \mu_y)/ \sigma_y) \quad (7)$$

where $\Phi(.)$ is the cdf of the standard normal distribution, μ_y and σ_y are mean and variance of y (= ln(x)), respectively.

In case of theoretical Weibull distribution, the equation is [33],

$$G(x) = 1 - \exp(x/\alpha)^{\kappa} \quad (8)$$

where α and κ are scale and shape parameters respectively. By the method of moment these parameters relate to the mean μ and variance σ as [2],

$$\mu = \alpha\Gamma(1 + 1/\kappa) \quad (9)$$

$$\sigma^2 = \alpha^2(\Gamma(1 + 2/\kappa) - (\Gamma(1 + 1/\kappa))^2) \quad (10)$$

where $\Gamma(.)$ is the gamma function.

The model equation for the generalized Pareto distribution is [33],

$G(x) = 1 - (1 - \kappa x/\alpha)^{1/\kappa}$ (11)

where the scale α and shape κ parameters, by the method of moment, are related to the mean μ and variance σ as [2],

$\mu = \alpha/(1 + \kappa)$ (12)

$\sigma^2 = \alpha^2/((1 + \kappa)^2(1 + 2\kappa))$ (13)

A return period is the reverse of exceedence probability as [31],

$T_{AMS} = 1/G(x)$ (14)

The derived return period T_{AMS} in Eq. (14) is for mas, but in our case we use pds therefore we have to estimate the return period based on pds as [2],

$T_{PDS} = - 1/\ln(1 -1/T_{AMS})$ (15)

where T_{PDS} is return period based on partial series data, and T_{AMS} is annual series data.

5. Evaluation

We evaluated hydrological drought frequency at 8 gauging stations along the Yom River from upstream to downstream i.e. Y.20, Y.1C, Y.14, Y.6, Y.3A, Y.4, Y.17, and Y.5. The discharges of daily average data series from 1998 to 2012 of all stations except Y.4 and Y.5 from 1990 to 1997 and from 1991 to 1997, respectively, were used to determine deficit volumes and flow duration curves. First, we constructed a flow duration curve for each station. Then, a series of deficit volumes for each station was determined and frequency analysis for each deficit volume series was made.

For flow duration curve construction, the daily flow data of each station were arranged in order from highest to lowest. The highest value marks as ranking 1 and the second ranking 2 and so on, or m = 1, 2, 3,......, n, to the lowest one, says, ranking n. Then we calculated the correspondent time percentile as:

$t = 100*m/(n+1)$ (16)

Normally, we plot the discharge values on Y-axis and the time percentile on X-axis, the discharge axis can be natural or logarithmic scales. Then we read the discharge value according to the percentile e.g. Q_{70} = 6.2 m^3/s means the flows of 6.2 m^3/s or higher are of 70 % of the time (Figure 3).

A series of deficit volumes were also calculated from the daily flow series Q_t and the threshold level Q_0. We accepted the threshold level as Q_{70} from the period-of-record flow duration curve. Whenever the discharge is lower than the threshold level then the flow is deficit. Total volume of the deficit discharges in each event is the deficit volume for that event. Eqs. 1-3 show how to calculate the deficit volume which mutual events are overcome by the sequent peak algorithm procedure [27]. Minor droughts can distort the result of frequency analysis [21], therefore they can be discarded when their deficit volume is smaller than 0.01 Mm^3. The series of deficit volumes of each station were ready to be analyzed.

We analyzed probability distributions of deficit volumes for the 8 stations using 3 theoretical models i.e. log-normal (Eq.7), Weibull (Eq. 8), and generalized Pareto (Eq. 11) models. Then, we compared these models to the empirical Weibull distribution (Eq. 6) to finalize the best model. The results of the best distribution were used for return period estimations (Eq. 14). The return period resulted from Eq. (14) is not the true value because the data series were not annual maximum series. Therefore, the return periods from Eq. (14) were transformed to the actual ones by Eq. (15).

6. Results and discussions

The flow duration curve of each station was plotted as Figure 3, for example, then Q_{70} of each station was determined. Q_{70} of all stations are shown in Table 2 to be used as threshold levels. When the data from Y.4 and Y.5 are ignored the average threshold level is 7.77 m^3/s and its standard deviation is 1.37 m^3/s. The standard deviation of 1.37 m^3/s shows that low flow of the whole river is quite uniform. The lower values of Y.4 and Y.5 were ignored because their monitoring times (1990 - 1997) are different from the rest (1998 - 2012).

Table 2 Threshold levels Q_{70} from flow duration curves

Stations	Y.20	Y.1C	Y.14	Y.6	Y.3A	Y.4	Y.17	Y.5
Q_{70} (m^3/s)	6.2	6.2	9.7	8.3	7.8	2.7	8.4	0.9

Table 3 Series of deficit volumes of Y.20 from water year 1998 to 2012

Date	D (Mm^3)	Date	D (Mm^3)	Date	D (Mm^3)
14/5/98	8.92	12/5/03	0.25	2/4/09	11.89
17/4/99	41.6	16/6/03	0.12	15/5/10	44.14
22/4/00	13.02	5/5/04	31.89	24/4/11	29.41
9/3/01	6.91	1/5/05	31.55	10/3/12	5.10
3/5/01	4.69	19/4/06	21.02	3/4/12	1.16
3/5/02	21.59	29/4/07	32.89	27/4/12	0.26
15/3/03	2.76	31/1/08	4.16	20/2/13	0.10
23/4/03	1.33	15/4/08	15.56	4/3/13	0.07

Table 4 Average numbers of drought events per year

Stations	T.20	Y.1C	Y.14	Y.6	Y.3A	Y.4	Y.17	Y.5	Average
Event/year	1.60	2.00	2.47	1.13	1.87	1.50	2.13	1.43	1.77

For every station, hydrological drought occurred every year at least one event annualy except some years more events happened. For example, Table 3 shows series of deficit volumes of Y.20 having 24 events during 15 years, therefore the average number of annual events is 1.6. The average numbers of events per year for all stations are shown in Table 4, which the highest value is for Y.14 of 2.47 events per year and Y.6 the lowest 1.13 events per year. The average value for all stations is 1.77 annual events.

The series of deficit volumes, such as in Table 3, were used for calculating three theoretical probability distributions, i.e. lognormal, Weibull, and generalized Pareto. Then, they were compared to the empirical distribution of Weibull as in Figure 6 for Y.20. We applied the coefficient of determination R^2 to decide the best theoretical model as in Table 4. Figure 6 illustrates equally good matching of both Weibull and generalized Pareto with the empirical distribution. Lognormal distribution does not give a good result. The theoretical distribution of Weibull is preferable to generalized Pareto as shown in Table 5, therefore theoretical Weibull was chosen for frequency analyses in the study.

Table 5 Comparison of R^2 for three theoretical models

Stations	The value of R^2		
	LN	**Wei**	**GP**
Y.20	0.627	0.948	0.947
Y.1C	0.980	0.929	0.909
Y.14	0.559	0.920	0.912
Y.6	0.954	0.972	0.969
Y.3A	0.683	0.940	0.933
Y.4	0.995	0.972	0.971
Y.17	0.663	0.945	0.946
Y.5	0.913	0.967	0.971
Average	0.797	0.949	0.945

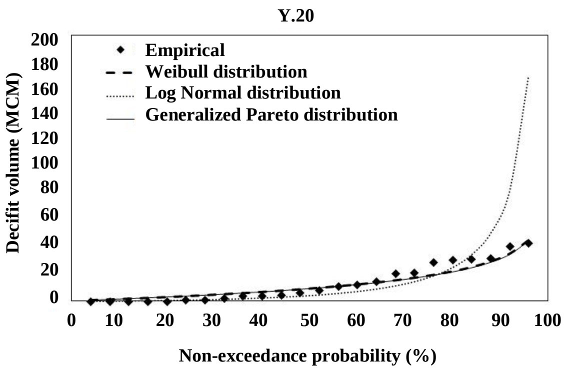

Figure 6 Comparison of 3 theoretical distributions with empirical Weibull for Y.20

The results of hydrological drought frequency analyses using theoretical Weibull distribution show, as in Figure 7, the distributions for almost all stations are arranged in an orderly manner, except Y.1C, with Y.17 with the most severe drought then Y.14, Y.6, Y.3A, Y.20, Y.4, and Y.5 the least. The result of Y.1C shows a strange distribution compared to others. It is almost smallest at 2-year return period, then climbs up to be more severe than Y.5 and Y.4 at 10-year, moreover at 20-year return period the drought severity of Y.1C is higher than Y.5, Y.4, and also Y.20 (Figure 7). The station Y.1C is at the city of Phrae with a weir across the river at downstream of the city. The river water from this section is used for city water supply and irrigation of small patches of paddy fields (Figure 8). At smaller drought, paddy fields are rainfed to save pumping power but at larger drought, they are irrigated. This can make the distribution of Y.1C to be nonuniform compared to others.

Figure 8 shows the deficit volumes at 20-year return period for all stations along with their locations on the Yom River. It demonstrates that the drought is less severe at the upstream station Y.20 (39 Mm^3), and gradually increasing to Y.1C (44 Mm^3) and to peak at Y.14 (86 Mm^3), then gradually decreasing to Y.6 (68 Mm^3), Y.3A (52 Mm^3), then to Y.4 (31 Mm^3) and peaks again to the highest severity at Y.17 (112 Mm^3) then abruptly drops down to the least severe at station Y.5 (10 Mm^3). Since paddy fields become larger toward downstream, drought becomes more severe approaching downstream, demonstrated by the deficit volumes of 39, 44, and 86 Mm^3 of the stations Y.20, Y.1C, and Y.14, respectively. Definitely, larger paddy field areas need more irrigated water causing more severe drought.

When considering Y.6, Y.3A, and Y.4 which having drought deficit volumes of 68, 52, and 31 Mm^3, respectively toward downstream following from Y.14 (Figure 8), their deficit values do not getting larger toward downstream, instead they become smaller. Figure 8 shows the wellfield and groundwater irrigation areas covering from Y.6 to Y.4, with Y.3A at the center [36]. The paddy fields in the groundwater project area receive most of deep groundwater for irrigation with roughly uniform distribution. This deep groundwater compensates utilizing surface water from the Yom River, making droughts of these three stations are less severe than those of Y.14 and Y.17. The return flow from the irrigation water makes the severity of drought decreasing along the Yom in the project area. This irrigation project is one of the largest deep groundwater utilization in Thailand [36]. The wellfield abstracts most of the baseflow which might have been feeding to the river section along the station Y.17 in the dry season. At the same time, this river section responsible for surface water irrigating large paddy field areas (Figure 8). These can raise drought severity of this river section, therefore the deficit volume at Y.17 is the highest of all. Van Lanen et al. [37] assessed the impacts of climate, soil, and groundwater on the hydrological drought. They found hydrological drought is very sensitive to groundwater change. This reminds us of an old saying that *there ain't no such thing as a free lunch*. When the upstream paddy field farmers enjoy cheap groundwater irrigation, provided by Government, the downstream farmers suffer from water scarcity.

The station Y.5 is close to the confluence with the Nan River less than 15 km, and that with the Ping River less than 30 km (Figure 8). The Ping and the Nan take most the responsibility for irrigating the areas while the Yom does not. The back waters from the two rivers also liftup the flow in the Yom at Y.5. Therefore the Yom River section along Y.5 is possible to hold the rank of lowest drought severity.

From the above frequency analyses of streamflow drought along the Yom River, we found two locations with the heaviest burden, around the stations Y.14 and Y.17, both are closest to but still relatively far away from the deep groundwater irrigation areas; the former is further upstream while the latter downstream. not to mention Y6, Y3A, and Y.4 which are considered to be inside the irrigation area (Figure 8). To alleviate droughts in these locations, better water management in these areas are needed. The surplus water in the wet season can be harvested and stored for use in the dry season. The amount and method of storing water depend on risk acceptance and the suitability of the site, whether using surface or groundwater storages or both in conjunction [6],[30],[38]. The findings of this study can help planners and engineers quantify the amount of water to be reserved in the rainy season at each critical locations.

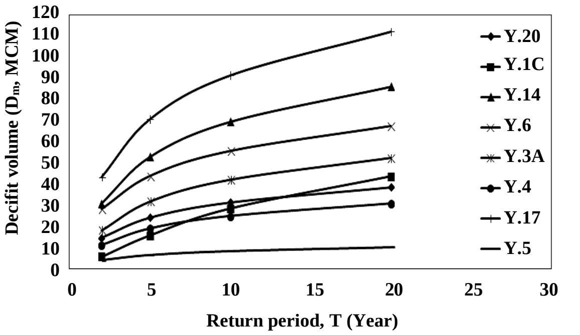

Figure 7 The deficit volumes at several return periods of all stations

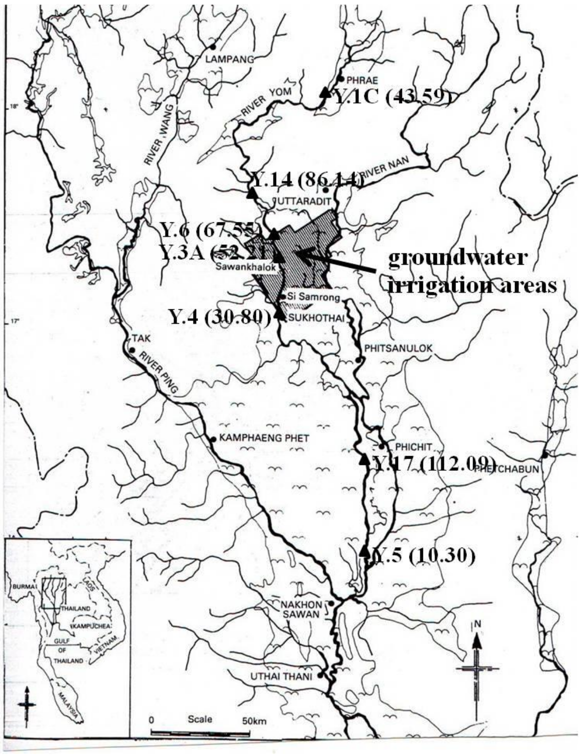

Figure 8 The deficit volumes at 20-year return period along the Yom, the numbers in brackets are deficit volumes (in Mm^3) at 20-year return period(modified from [36]).

7. **Conclusions**

The Yom River is subjected to streamflow drought every year with varying degree of severity along the main course. We have performed frequency analyses at 8 stations along the river using deficit volumes to quantify drought events. Theoretical Weibull cumulative distribution function was chosen to compare deficit volumes at 2-, 5-, 10-, and 20-year return periods from partial duration series for all stations. The first three upstream stations show increasing in drought severity downstream-ward since their irrigation areas getting larger. However, the next three stations downstream are contradictory showing drought to decline, due to the deep groundwater irrigation substituting for their streamflow irrigation and coupling with irrigation return flow. The next one further downstream, the station Y.17, is the worst, due to its baseflow being cut off by groundwater abstraction. Then the last one at downstream-most, Y.5, is the least drought severity because most of irrigating waters in its areas come from the other bigger rivers, the Ping and the Nan. To combat drought of the Yom, wet season water have to be stored for dry spell utilization, especially around Y.14 and Y.17. The quantity of reserved water at each location depends on risk acceptance which has been concerned in this study and site characteristics.

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9. References

[1] Wilhite DA. Droughts as a natural hazard: concepts and definitions. In: Wilhite DA, editor. Drought: a global assessment, vol I, routledge hazards and disasters series. London: Routledge; 2000. p.3-18.

[2] Tallaksen LM, Van Lanen HAJ. Hydrological drought: processes and estimation methods for streamflow and groundwater, developments in water science 48. Amsterdam: Elsevier; 2004.

[3] Lake PS. Drought and aquatic ecosystems: effects and responses. Hoboken: Wiley-Blackwell; 2011.

[4] Van Loon AF. Hydrological drought explained. WIREs Water. 2015;2(4):359-92.

[5] Mishra AK, Singh VP. A review of drought concepts. J Hydrol. 2010;391:202-16.

[6] Pavelic P, Srisuk K, Saraphirom P, Nadee S, Pholkern K, Chusanathas S, Munyou S, Tangsutthinon T, Intarasut T, Smakhtin V. Balancing-out floods and droughts: opportunities to utilize harvesting and groundwater storage for agricultural development in Thailand. J Hydrol. 2012;470-471:55-64.

[7] Sharma TC, Panu US. Modeling of hydrological drought durations and magnitudes: experience on Canadian streamflows. J Hydrol Reg Stud. 2014;1:92-106.

[8] Van Huijgevoort MHJ, Van Lanen HAJ, Teuling AJ, Uijlenhoet R. Identification of changes in hydrological drought characteristics from a multi-GCM driven ensemble constrained by observed discharge. J Hydrol 2014;512:421-34.

[9] Chuenchooklin S, Ichikawa T, Patamatamkul S, Sriboonlue V, Kerdpitaksa C. Phreatic surface fluctuations within the tropical floodplain paddy field of the Yom River, Thailand. Hydrol Earth Syst Sci Discuss. 2005;2:731-60.

[10] Divakar L, Babel MS, Perret SR, Das Gupta, A. Optimal allocation of bulk water supplies to competing use sectors based on economic criterion - an application to the Chao Phraya River Basin, Thailand. J Hydrol. 2011;401:22-35.

[11] Molle F. Scales and power in river basin management: the Chao Phraya River in Thailand. Geogr J. 2007;

173(4):358-73.
[12] Petchprayoon P, Blanken PD, Ekkawatpanit C, Hussein K. Hydrological impacts of land use/land cover change in a large river basin in central-northern Thailand. Int J Climatol. 2010;30:1917-30.
[13] Dracup JA, Kil Seong L, Paulson Jr EG. On the statistical characteristics of drought events. Water Resour Res. 1980;16(2):289-96.
[14] Kim T, Valdes J, Yoo C. Nonparametric approach for estimating return periods of droughts in arid regions. J Hydrolog Eng. 2003;8(5):237-46.
[15] Wong G, Van Lanen HAJ, Torfs PJJF. Probabilistic analysis of hydrological drought characteristics using meteorological drought. Hydrolog Sci J. 2013;58(2): 253-70.
[16] Van Loon AF, Laaha G. Hydrological drought severity explained by climate and catchment characteristics. J Hydrol. 2015;526:3-14.
[17] Sung JH, Chung ES. Development of streamflow drought severity-duration-frequency curves using the threshold level method. Hydrol Earth Syst Sci. 2014;18:3341-51.
[18] Yevjevich V. An objective approach to definition and investigation of continental of hydrologic droughts. Fort Collins: Colorado State University; 1967.
[19] Clausen B, Pearson, CP. Regional frequency analysis of annual maximum streamflow drought. J Hydrol. 1995;173:111-30.
[20] Hisdal H, Tallaksen LM, Clausen B, Peters E, Gustard A. Hydrological drought characteristics. In: Tallaksen, LM, van Lanen HAJ, editors. Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater, Developments in Water Science 48. Amsterdam: Elsevier; 2004.
[21] Tallaksen LM, Madsen H, Clausen B. On the definition and modelling of streamfloiw drought duration and deficit volume. Hydrolog Sci J. 1997;42(1): 15-33.
[22] Wanders N, Wada Y. Human and climate impacts on the 21st century hydrological drought. J Hydrol. 2015;526:208-20.
[23] Shaw E, Beven KJ, Chappell NA, Lamb R. Hydrology in practice. 4th ed. London: Spon Press; 2011.
[24] Sugiyama H, Vudhivanich V, Ngernprasertsri S, Lorsirirat K. Hydrologic drought characteristics of the upstream reaches of the Mae Klong River. Workshop on Sustainable Development of Agricultural Infrastructure and Organizational Management of Chao Phraya and Mae Klong Basins; 1998 Oct 30; Bangkok, Thailand; 1998. p. 1-15.
[25] Vogel RM, Fennessey NM. Flow-duration curves. I: new interpretation and confidence intervals. J Water Resour Plann Manag. 1994;120(4):485-504.
[26] Tallaksen LM, Madsen H, Hisdal H. Frequency analysis. In: Tallaksen, LM, van Lanen, HAJ, editors. Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater, Developments in Water Science 48. Amsterdam: Elsevier; 2004.
[27] Fleig AK, Tallaksen LM, Hisdal H, Demuth S. A global evaluation of streamflow drought characteristics. Hydrol Earth Syst Sci. 2006;10:535-52.
[28] Zelenhasic E, Salvai A. A method of streamflow drought analysis. Water Resour Res. 1987;23(1):156-68.
[29] Vogel RM, Stedinger JR. Generalized storage-reliability-yield relationships. J Hydrol. 1987;89:303-27.
[30] McMahon TM, Vogel RM, Pegram GGS, Peel MC, Etkin D. Global streamflows - part 2: reservoir storage-yield performance. J Hydrol. 2007;347:260-71.
[31] Chow VT, Maidment DR, Mays LW. Applied hydrology. New York: McGraw-Hills; 1988.
[32] Begueria S. Uncertainties in partial duration series modeling of extremes related to the choice of the threshold value. J Hydrol. 2005;303:215-30.
[33] Yahiauoi A, Touaibia B, Bouvier C. Frequency analysis of the hydrological drought regime: case study oued Mina catchment in western of Algeria. Nat Tech J. 2009;1:3-15.
[34] Jain VK, Jain MK, Pandey RP. Effect of the length of streamflow record on truncation level for assessment of streamflow drought characteristics. J Hydrolog Eng. 2014;19(7):1361-73.
[35] Kim S, Kim H, Kwak J, Kim Y, Noh H, Lee J. Analysis of drought length using the DBS static and close returns test. KSCE J Civ Eng. 2015;19(2):446-55.
[36] Shaw EM. Engineering hydrology techniques in practice. New York: Wiley; 1989.
[37] Van Lanen HAJ, Wanders N, Talaksen LM, Van Loon AF. Hydrological drought across the world: impact of climate and physical catchment structure. Hydrol Earth Syst Sci. 2013;17:1715-32.
[38] Chuchooklin S, Mekpruksawong P, Chidchob P. The river analysis simulation model for the planning of retention area and diversion channel for flood reduction in the Lower Yom's River Basin, Thailand. 4th INWEPF Steering Meeting and Symposium; 2012 Jul 5-7; Bangkok, Thailand; 2012. p. 1-13.