WATER BALANCE FOR ANALYZING THE DEPLETION OF RESERVOIR INFLOWS

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Abstract:

The main objective of this study is to propose a simple water-balance scheme for analyzing the depletion of reservoir inflows. The diminishing reservoir inflows are the total sum of decreasing rainfall excesses due to deforestation, as usually considered in most previous studies, and increasing irrigation and domestic requirements within each sub-basin. The proposed scheme was applied to analyze the inflows of the Bhumiphol Dam. The records of 44-year (1955 – 1998) annual flows, 23-year (1975 – 1997) annual rainfalls, 19-year (1979 – 1997) irrigation areas, and 15-year (1983 – 1997) population numbers were used. Results have demonstrated that the reduction of reservoir inflows is mainly attributed to the decreasing rainfall excesses in the Ping-2 Sub-basin, and the increasing irrigation requirements in the Mae Li one. Further, it is concluded that the proposed water-balance scheme is feasible for the analysis of depleting reservoir inflows.

1. Introduction

Most major reservoirs in Thailand have recently experienced the severe depletion of their limited available inflows. The critical situation consequently leads people residing within the watershed area downstream to the reservoirs to face serious water shortages in the dry season frequently. Recent examples are the severe drought events in The Chao Phraya River Basin during 1993 and 1998, which result from the decrease of inflows to the Bhumiphol Dam.

In order to conserve the limited available amount of reservoir inflows, it is therefore necessary to determine the principal causative factors of inflow reduction so that effective measures can be planned and implemented. Most previous investigations attempted to show that the inflow depletion was attributed to the continuation of deforestation process in the drainage area {see, e.g., [1] and [2]}. It is generally known that the deforestation phenomenon usually reduces the average rainfalls over the area, and consequently decreases its reservoir inflows. Unfortunately, considering only the referred factor did not give a good description on depleting reservoir inflows.

The main objective of the present study is to propose a water balance concept for analyzing the depletion of reservoir inflows. Hence, the decreasing reservoir inflow is defined as the total sum of decreasing rainfall excesses, and increasing irrigation and domestic demands for all sub-watershed areas of the reservoir. Results of an illustrative application using the observed rainfall, runoff, and relevant data of the Bhumiphol Dam have indicated that the proposed scheme describes the depletion of the reservoir inflows adequately.

2. Water Balance of Depleting Reservoir Inflows

Let X_t be the totally annual inflow record to a reservoir during year t (t = 1, 2, ..., n; where n is the period of available flow data). The approach starts to fit a linear regression to X_t as

$$X_{t+1} = Q.X_t + Q' \qquad (1)$$

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where Q and Q' are a slope and intercept parameters respectively. The constants Q and Q' are estimated by the technique of least squares using the observed flow record X_t. The slope Q must be negative in case of inflow depletion.

If we divide the whole reservoir watershed area into m sub-basins (m = the total number of sub-basins), the decreasing flow rate Q shall be written as

$$Q = \sum_{i=1}^{m} Q_i \qquad \textbf{(2)}$$

in which Q_i = the rate of increasing or decreasing flows per year for sub-basin i (i.e., $Q_i > 0$ or $Q_i < 0$). Rearrange **(2)** to obtain the overall decreasing rate S of reservoir inflows as

$$S = \sum_{j=1}^{l} Q_j \qquad \textbf{(3)}$$

where l is the total number of sub-basins whose $Q_j < 0$.

The total decreasing-flow rate S is attributed to the reduction of average annual rainfall depths, and the increasing diverted flows due to irrigation and domestic uses within each sub-basin of the reservoir considered. That is,

$$S = \sum_{j=1}^{l} \left(E_j + I_j + D_j\right) \qquad \textbf{(4)}$$

in which E_j = the rate of decreasing rainfall excess per year for sub-drainage area j, I_j = the rate of increasing irrigation requirement per year in the j'th area, and D_j = the rate of additional water supply per year within the j'th basin. Note that **(4)** does not take into account of several water uses (i.e., industrial and recreation water demands) because the whole basin of most reservoirs is usually in the remote area where such requirements are negligible.

The decreasing rainfall excess rate E_j is estimated as

$$E_j = \Phi_j . R_j \qquad \textbf{(5)}$$

where R_j is the slope of linear regression model of $Y_{j,t}$ in which $Y_{j,t}$ = the average rainfall depth during year t over sub-basin j, and Φ_j is the slope of linear relationship between cumulative flow $\sum_t X_{j,t}$ and average rainfall $\sum_t Y_{j,t}$. Notice that **(5)** is applicable, when $R_j < 0$. The mean rainfall $Y_{j,t}$ is calculated by the Thiessen method using the annual rainfall data of stations locating within and around the considered basin {see, [3]}:

$$Y_{j,t} = \sum_{k=1}^{p} W_k Y_{k,t} = \sum_{k=1}^{p} \frac{A_k}{A_j} Y_{k,t} \qquad \textbf{(6)}$$

in which $Y_{k,t}$ = the record of annual rainfall at station k during year t, A_k = the polygon area enclosing station k, A_j = the area of sub-basin j, and p = the total number of rainfall gauging stations used.

To estimate the rate I_j of increasing irrigation requirements per year for sub-drainage area j; let $Z_{j,t}$ be the irrigation area during year t within drainage basin j, G_j be the fitted slope of $Z_{j,t}$, and Γ_j be the irrigation demand per unit area. The rate I_j is hence given as

$$I_j = \left(-G_j\right)\Gamma_j \qquad \textbf{(7)}$$

The negative sign in **(7)** is used because the rate I_j results in depleting the reservoir inflows. Similarly, the rate D_j of increasing domestic use per year results from the product of Λ_j and H_j in which H_j = the increasing rate per year of population P_j, and Λ_j = the amount of water required per capita [see, e.g., (7)].

3. Illustrative Application

The approach described earlier was applied to the Bhumiphol drainage basin. Figure 1 shows its watershed area, and the locations of all flow and rainfall gauging stations used in this study. The lengths of obtained flow and rainfall records are 44 years (1955 – 1998) and 23 years (1975 – 1997) respectively. While, the periods of 19-year (1979 – 1997) irrigation area data and 15-year (1983 – 1997) population records are available.

Table 1 presents the fitted linear regression models of observed annual flows for all sub-basins of the Bhumiphol watershed area. It is readily seen that the overall decreasing-flow rate S calculated using **(3)** is verified. Its value is between –51 and –54 mcm/yr. Further, it appears that the available flows of most sub-basins (e.g., Mae Ngad, Mae Rim, Ping-2, Mae Kuang, Mae Chaem, Mae Klang , and Mae Li) are decreasing.

Tables 2 and 3 show the linear regression parameters of several relevant variables (e.g., rainfall, rainfall-runoff, irrigation area, and population number) for the referred sub-basins. Table 4 illustrates the rates of decreasing rainfall excesses, increasing irrigation and domestic requirements of the considered sub-drainage areas. It is evident that the increasing domestic use D_j is quite small as compared with the decreasing rainfall excess E_j and increasing irrigation requirement I_j. This means that the decreasing inflows of the Bhumiphol dam are mainly caused by the rainfall excess E_j and irrigation demand I_j. The greatest rainfall reduction appears to be in the Ping-2 Sub-basin. The Mae Li Sub-basin is the area where many irrigation projects are developed. Further, it indicates that the proposed analyzing scheme describes well the depletion of Bhumiphol inflows. The grand total of the three rates for these sub-basins is - 58.4 mcm/yr which is approximately 6% of average annual inflows. It is quite close to that observed from the reservoir inflow records.

4. Summary and Conclusions

The analysis of decreasing reservoir inflows is usually necessary for conserving the limited available water to be used within the watershed area downstream to the reservoir. Previous studies usually considered the depletion of reservoir inflows to mainly depend on deforestation phenomenon. However, this consideration failed to yield the reservoir inflows accurately.

This paper, therefore, proposes a simple water-balance scheme for analyzing the depletion of reservoir inflows. The proposed scheme defines the whole diminishing inflows as the sum of decreasing rainfall excesses, and increasing irrigation and domestic requirements in every sub-basin. It was applied to analyze the rate of depleting inflows of the Bhumiphol Dam using the records of 44-year (1955 – 1998) annual flows, 23-year (1975 –1997) annual rainfall, 19-year (1979 –1997) irrigation areas, and 15-year (1983 – 1997) population numbers. Results have indicated that the inflows of the Bhumiphol Dam deplete mainly due to the decrease of rainfall excesses in the Ping-2 Sub-drainage Basin, and the increase of irrigation requirements in the Mae Li one. The calculated decreasing inflows agree well with the observed ones. It is thus concluded that the proposed scheme is feasible for analyzing the depletion of reservoir inflows.

5. Acknowledgements

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Figure 1 The Ping Watershed Area, and the Locations of Flow and Rainfall Stations

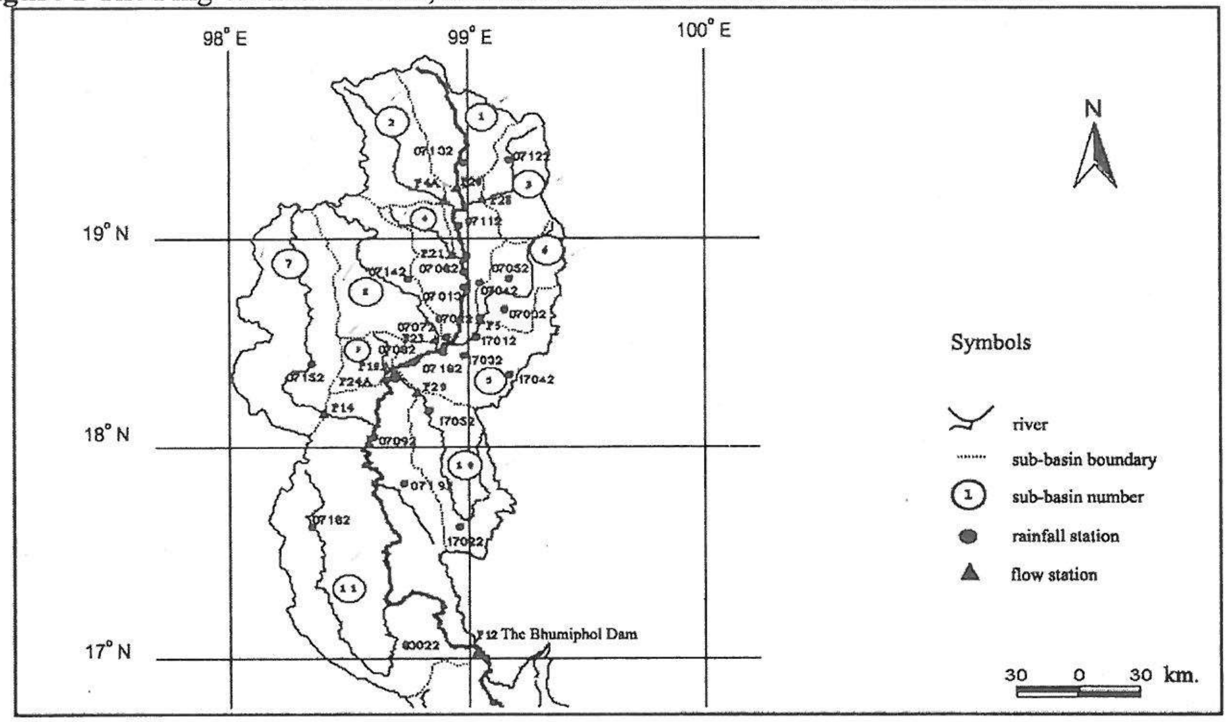

Table 1 Linear Regression Parameters of Annual Flow Series ($X_{i,t}$ and t) for the Bhumiphol Watershed Areas.

Number	Basin	Sub-basin	Station	Slope, mcm/yr. $Q_i > 0$	Slope, mcm/yr. $Q_i < 0$	Intercept, mcm
1		Ping-1	P.20	4.1		355.9
2		Mae Taeng	P.4A	10.1		573.5
3		Mae Ngad	P.28		-2.6	404.9
4		Mae Rim	P.21		-0.7	158.1
5		Ping-2	P.19A		-19.7	3,405.8
6		Mae Kuang	P.5		-10.9	897.2
7		Mae Chaem	P.14		-4.1	1,248.4
8		Mae Khan	P.23	3.6		385.6
9		Mae Klang	P.24A		-3.2	207.2
10		Mae Li	P.29		-9.5	272.4
11	Upper Ping		P.12		-36.2	6,530.3
	S, mcm/yr			-54.0*	-50.7**	

* The overall rate S is -36.2 - (4.1+10.1+3.6) = -54.0 mcm/yr.

** The overall rate S is –(2.6+0.7+19.7+10.9+4.1+3.2+9.5) = -50.7 mcm/yr

Table 2 Linear Regression Parameters of Average Annual Rainfall Series ($Y_{j,t}$ and t) and Cumulative Rainfall-Runoff Variables ($\sum_t X_{j,t}$ and $\sum_t Y_{j,t}$) for the Sub-basins with $Q_j < 0$.

Number	Sub-basin	Rainfall		Rainfall-Runoff	
		Slope, mm/yr.	Intercept, mm	Slope, mcm/mm	Intercept, mcm
3	Mae Ngad	9.9	907.8	-	-
4	Mae Rim	9.5	929.6	-	-
5	Ping-2	-7.7	1,064.2	2.7	2,938.0
6	Mae Kuang	-5.9	1,009.9	0.5	917.3
7	Mae Chaem	-0.8	676.5	1.5	425.0
9	Mae Klang	-3.5	764.4	0.2	60.5
10	Mae Li	-0.5	897.0	0.2	150.0

Table 3 Linear Regression Parameters of Sequences of Irrigation Area ($Z_{j,t}$ and t) and Population ($P_{j,t}$ and t) for the Sub-basins with $Q_j < 0$.

Number	Sub-basin	Irrigation Area		Population	
		Slope, Rai/yr	Intercept, Rai	Slope, No/yr	Intercept, No
3	Mae Ngad	4,440	6,666	1,396	54,515
4	Mae Rim	1,465	8,611	1,309	51,115
5	Ping-2	1,465	4,175	8,808	344,009
6	Mae Kuang	6,556	25,263	2,967	407,337
7	Mae Chaem	1,464	11,250	1,243	48,565
9	Mae Klang	1,187	12,702	1,142	44,587
10	Mae Li	19,922	6,250	2,989	116,751

Table 4 Rates of Decreasing Rainfall Excesses (E_j), and Increasing Irrigation and Domestic Requirements (I_j and D_j) for the Sub-drainage Areas with $Q_j < 0$ in mcm/yr.

Number	Sub-basin	Rainfall	Irrigation	Domestic	Total
3	Mae Ngad	-	-3.8	-0.1	-3.9
4	Mae Rim	-	-1.3	-0.1	-1.4
5	Ping-2	-20.8	-1.3	-0.4	-22.5
6	Mae Kuang	-3.0	-5.7	-0.1	-8.8
7	Mae Chaem	-1.2	-1.3	-0.1	-2.6
9	Mae Klang	-0.7	-1.0	-0.1	-1.8
10	Mae Li	-0.1	-17.2	-0.1	-17.4
	Grand Total				-58.4

The irrigation demand per unit area Γ_j is 865.1 m^3/Rai {see [4]}.

The amount of domestic water required per capita Λ_j is 120 litre/day/capita {see [5]}.