〈論　文〉

수문학적 응용을 위한 강우량 산정
Rainfall Estimation for Hydrologic Applications

배 덕 효*
BAE Deg-Hyo

Abstract□ The subject of the paper is the selection of the number and location of raingauge stations among existing ones, which will be part of real-time data collection system, for the computation of mean areal precipitation and for use as input of real-time flow forecasting models. The weighted average method developed by National Weather Service was used to compute MAP. Two different searching methods were used to find local optimal solutions as a function of the number of raingauges. An operational rainfall-runoff model was used to determine the optimal location and number of stations for flow prediction.

요　지 : 본 연구의 목적은 실시간 자료수집 시스템의 일환으로서 어떤 유역에 존재하는 기존의 강우관측지점으로부터 유역평균강우량을 산정할 때나 이를 강우-유출 모형의 입력치로 사용할 때 필요한 강우관측지점의 수와 위치를 선정하는 방법을 제시하였다. 유역평균강우량 산정방법은 미국 국립기상청이 제안한 가중치방법을 사용하였다. 강우관측지점 수에 따른 국부적인 최적위치선정은 서로 다른 두가지 방법으로 추적되었다. 유량예측을 위한 강우관측지점의 최적위치와 수를 결정하기 위하여 실제 실무에서 적용하고 있는 강우-유출 모형을 사용하였다.

1. Introduction

Precipitation varies in time and space driven by the patterns of atmospheric circulation and influenced by local conditions. Accurate estimation of precipitation is one of the most important study areas in hydrology because of the many applications that the rainfall estimates have. The capability of precipitation measured at a single gauge in representing the mean areal precipitation (MAP) over a study area is a function of topography, the size of the study area, the distance from the gauge to the center of the representative area, and the local storm patterns.

A problem that arises with the establishment of real-time databases by federal, state and local agencies in support of real-time flood forecasting and warning is the issue of selecting raingauge sites (among existing sites) which will be part of the real-time data collection system. Selection is based on the degree that the site data would improve MAP estimation over the watersheds of interest. Many hydrologists developed methods for estimating MAP over a watershed from raingauge data (Thiessen, 1911; Reed and Kincer, 1917; Linsley, et al., 1958). In most cases, the estimation of MAP for a certain time is based on a weighted-average method. Typical estimation methods are the arithmetic average method, the

---

* Member, Engineering Research Institute, Yonsei University, Senior Researcher

Thiessen polygon method and the isohyetal method. The simplest one is the arithmetic average method that uses equal weights for all the stations. This method does not consider orographic effects and spatial variations of raingauge density. It is, therefore, only useful if raingauges are uniformly distributed in a flat area. The Thiessen polygon method is a weighted average method using the ratio of dominant subbasin area for a station to total area as a weight in estimating MAP. This method is not suitable for mountainous areas because of orographic effects. The isohyetal method is based on the interpolation of rainfall between raingauges via the construction of constant rainfall contours. The weighting factor can be obtained from the ratio of subbasin area between isohyets to total area. The isohyetal method is the most accurate approach, but it requires a skilled analyst and careful attention to topographic and other factors that have an impact on areal rainfall variability. Singh and Chowdhury (1986) compared 13 different methods including the aforementioned three methods for the estimation of MAP in two different areas. They conclude that all methods yielded comparable estimates, especially for annual rainfall values.

The purpose of the study is two fold: (a) to develop an optimization algorithm to select a given number of stations, among a set of existing raingauge stations, that would provide the most accurate MAP over an area; and (b) to solve the analogous problem when the objective is accurate real-time flow forecasting (rather than MAP estimation). For the purpose of examining the relative worth of the existing raingauge stations, optimization methods that find the optimal location of raingauge stations with respect to a set objective were developed. The best estimate of MAP is compared with those utilizing various subsets of all the raingauge stations systematically using one of two schemes: a global searching method and a forward searching method. The performance of these searching schemes of course depends on the study objective, accuracy requirements, and resources available for computation. For a given number and location of stations a procedure for computing MAP and a rainfall-runoff model for computing flow prediction are used to evaluate the accuracy of MAP estimation and flow prediction.

2. Optimal Locations of Raingauges for MAP Computation

As a first step toward finding the optimal number and location of raingauge stations, a preliminary study is required that considers: (1) the MAP computation method, (2) topography and the size of the basin area, (3) existing raingauges, and (4) the spatial raingauge distribution. The first item will be presented in the next section. The last three items will be discussed in section 4. One important consideration for the selection of raingauge location is the rainfall spatial pattern.

2.1 Computation of MAP

Although there are many methods to compute MAP over a certain area, a weighted-average method developed by the U.S. National Weather Service (NWS) was selected in this study (NWS, 1972). The reasons for the selection of this method are: (1) its simplicity for implementation of the objective function in Equation (7.a); (2) it compares favorably with the arithmetic average method because the latter does not consider the spatial distribution of raingauge locations; (3) the competing Thiessen polygon and isohyetal methods are

CPU intensive; and (4) it is in operational use by the NWS for real-time hydrologic applications.

Define by r(x,y) the spatial rainfall field over a given period of time, where x and y are the two orthogonal spatial coordinates. Then, the MAP over the study area (A) can be determined from

$$P=\frac{1}{A}\int_A r(x,y)\,dx\,dy \tag{1}$$

In practice, an approximation is made from point raingauge rainfall values because the continuous function r(x,y) can not be known precisely with present-day technology. Weather radar provides a promising alternative but in most field cases it has not been integrated with rainfall-runoff models, yet.

Using the NWS procedure, the estimated rainfall $\tilde{P}^t_{ij}$ in the center of the ijth grid at time t (see Figure 1) is expressed as follows:

$$\tilde{P}^t_{ij}=\sum_{k=1}^{N_P} W_{ijk}\,P^t_k \tag{2.a}$$

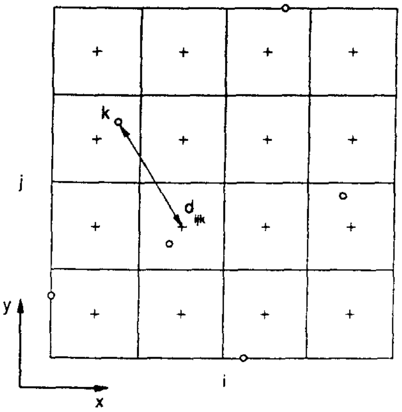

Fig. 1 Schematic diagram for the computation of mean areal precipitation(Note : "+" is center of discretised grid; and "o" is a location of raingauge station).

$$W_{ijk}=\frac{\frac{1}{d^2_{ijk}}}{\sum_{k=1}^{N_P}\frac{1}{d^2_{ijk}}} \tag{2.b}$$

$$\text{with } \sum_{k=1}^{N_P} W_{ijk}=1 \tag{2.c}$$

where, N_p is the number of raingauge stations and P^t_k, where $k=1 \cdots N_p$, $t=1 \cdots N_t$, is the observed rainfall value at station k over time step t. d_{ijk}, $i=1 \cdots N_x$, $j=1 \cdots N_y$, represents the distance from the center of the ijth grid to the kth raingauge station. W_{ijk} is a weight, which is a function of the inverse distance squared. The weighting factor W_{ijk} may have different forms depending on local rainfall patterns and duration. In general, the NWS recommends to use in Equation (2.b) as a weight for an estimate of the rainfall at a point as a weighted average of that at the surrounding raingauges and for the computation of MAP over an area. It is the result of unpublished development and experimentation over many years and has been verified on both an empirical and theoretical basis (NWS, 1972).

Let A_{ij} be the area of the ijth grid and $\sum\tilde{P}_t$ be the total rainfall over the study area. Then, the estimated mean areal rainfall (MAP_t) at time step t can be represented by

$$\sum\tilde{P}_t=\sum_{i=1}^{N_x}\sum_{j=1}^{N_y} A_{ij}\,\tilde{P}^t_{ij} \tag{3}$$

$$MAP_t=\frac{\sum\tilde{P}_t}{\sum\sum A_{ij}} \tag{4}$$

From these equations, an estimated MAP over the area averaged through all time steps will be

$$MAP=\frac{\sum_{k=1}^{N_t} MAP_t}{N_t} \tag{5}$$

If the areas of each grid square A_{ij} are the same, Equation (5) can be expressed as follows:

$$MAP=\frac{1}{N_t N_x N_y} \sum_{t=1}^{N_t}\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{k=1}^{N_p} W_{ijk} P_k^t \tag{6}$$

There are various levels of design identified for raingauge network design (Rodda, et al., 1969). Levels 1 and 2 are classified as regional estimation, while Level 3 accommodates special objectives such as flow forecasting. Levels 1 and 2 have no clearly defined final goal or objectives for the collected data and an example is the problem of estimating long-term averaged MAP. This study addresses the following specific questions:

(1) How many stations of an existing network of stations are needed to compute MAP for real-time flow forecasting in the study area?

(2) Which stations should be retained if all stations are not needed?

This study was performed under the following assumptions: (a) there exist enough raingauge stations in or near the study area; and (b) MAPs computed from all stations present the best estimate.

2.2 Optimization Model

2.2.1 Objective Function

In general, the objective of the optimization problem concerning raingauge network design is to minimize the cost, maximize the net benefits or both under required constraints. The objective used in this study was to maximize the accuracy of the estimation of MAPs, because of the fact that the scope of this study is limited to selecting the best raingauges from an existing network. For the design of Levels 1 and 2, the objective function is defined by the following equation, without any constraints:

$$F_{obj}=\mathrm{Min} \sum_{t=1}^{N_t} [\tilde{P}_{sa}-\tilde{P}_{sr}]^2 \tag{7.a}$$

$$\tilde{P}_{sa}=\frac{1}{N_x}\frac{1}{N_y}\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{k=1}^{N_p} W_{ijk} P_k^t \tag{7.b}$$

$$\tilde{P}_{sr}=\frac{1}{N_x}\frac{1}{N_y}\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{k'=1}^{N_p} W_{ijk} P_{k'}^t, \tag{7.c}$$

where, $\tilde{P}_{sa}$ is an estimated MAP that has been obtained using all existing raingauges, and N_r is the number of a certain combination of raingauge stations taken from N_p. So $\tilde{P}_{sr}$ represents the estimated MAP using a certain combination of raingauges. The value of the objective function (F_{obj}) represents the summation of quadratic error over a period of time consisting of N_t time steps (days in this work).

2.2.2 Search Procedure

To find the optimal solution, two different search methods were used: a global searching method (GSM) and a forward searching method (FSM). This concept has been applied in many other fields. For example, Rajagopal (1983, 1991) has applied this concepts for the detection of volatile organic compounds (VOCs) in ground water.

GSM is the procedure that evaluates the objective function systematically using all possible combinations of raingauges over the study area. A general characteristic of global searching is that no information from previous trials is used to determine the value of the decision variable in a subsequent trial. Therefore, it requires long computation time even if it guarantees the globally optimal solution. This method is useful for accurate estimation when the numbers of stations and test steps are small.

FSM is a kind of sequential searching procedure. It utilizes previous results to choose the values of the decision variables in subsequent trials. This method finds the best location of each number of raingauge stations sequentially. Let $\tilde{P}^t_{sr}$ $(S_n; N_i, N_i, \cdots\cdots, N_m)$ be the estimated MAP at time t from n raingauges with index numbers $N_i, N_i, \cdots\cdots, N_m$. B_{P_l} is minimum value of the objective function obtained from a subset of j raingauges in and around the study area. Then, the local optimal location of raingauges that gives minimum quadratic error between $\tilde{P}^t_{sa}$ and $\tilde{P}^t_{sr}$ $(S_l; N_k)$ from only one station is found from

$$B_{P_l} = \text{Min} \sum_{t=1}^{N_t} [\tilde{P}^t_{sa} - \tilde{P}^t_{sr}(S_l; N_k)]^2$$
$$k = 1, 2, 3, \cdots\cdots, N_p \qquad (8)$$

After finding B_{P_l}, the procedure searches sequentially for $B_{P_{2|k}}$, which is the minimum of the objective function for 2 stations including the station k that has given B_{P_l}.

$$B_{P_{2|k}} = \text{Min} \sum_{t=1}^{N_t} [\tilde{P}^t_{sa} - \tilde{P}^t_{sr}(S_2; N_j \mid N_k)]^2$$
$$j \neq k,\ j = 1, 2, 3, \cdots\cdots, N_p \qquad (9)$$

where, $\tilde{P}^t_{sr}$ $(S_2; N_j \mid N_k)$ represents the estimated MAP obtained from j and k stations. This procedure is followed sequentially until $B_{P_{N_p-1|\Sigma}}$ is found.

FSM does not guarantee the global optimal solution as GSM does. However, it takes only $\left(\sum_{r=2}^{N_p} r\right) - 1$ computations to find a local optimum while the global searching method requires $\sum_{r=1}^{N_p-1} C_{N_p, r}$ computations. $C_{N_p, r}$ denotes the number of combinations of N_p elements taken r at a time. FSM is often very useful in cases of many stations and for long time periods, or for a preliminary study.

3. Sparse Raingauge Effects for Flow Prediction

One of the objectives of this study is to observe the accuracy of flow computations as a function of the selected raingages. The accuracy of flow computation at the basin outlet is quantified in terms of the cross correlation coefficient (ρ_c) between observed and computed discharge.

The deterministic rainfall-runoff model used in this case is composed of the Sacramento soil moisture accounting model (Burnash et al., 1973; Peck, 1976; Armstrong, 1978; Kitanidis and Bras, 1980a,b; Georgakakos, 1986) and the conceptual kinematic stream routing model (Georgakakos and Bras, 1982a,b) applied to a headwater basin. Conceptual temperature index snowmelt (Anderson, 1973) and frozen ground

(Anderson and Neuman, 1984) models were also used in this study. It requires MAP and potential evapotranspiration data as inputs, and produces estimated flow at the drainage basin outlet as an output. The model components are based on operational hydrologic models used by the NWS. Bae and Georgakakos (1992) provides the details of the formulation of the model.

4. Case Study

4.1 Description of Study Basin and Data

The study area is the Boone River basin located in north central Iowa. It is approximately 100km north of Des Moines, Iowa. The Boone River joins the Des Moines River near Stratford. The area of the drainage basin is 2,160km^2 with outlet at Webster City, Iowa. The elevation ranges from 260 to 330 m above mean sea level. This terrain consists of cultivated corn fields and has generally mild slope which contributes to long response time for the basin.

For the purpose of finding the optimal location of raingauge stations, 11 raingauge stations were used in or near the Boone River basin, as shown in Figure 2. The double dot-dash line shows the boundary of the basin. As it can be seen in the figure, the raingauges are uniformly distributed over the area and are located in the basin or near its western boundary. The reason to include raingauges near the left boundary of the basin is that rain storms move from the West to the East. The boundary limits

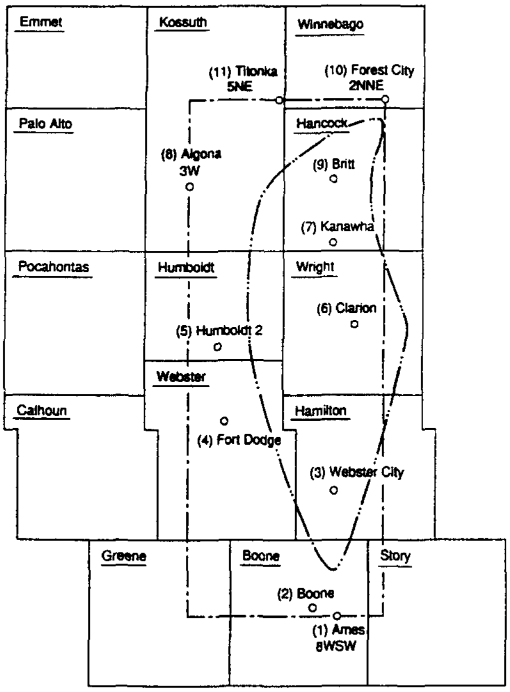

Fig. 2 Location of raingauge stations in or near the Boone River Basin.

Table 1. Locations of raingauge stations and data availability.

No.	Station Name	Latitude (West)	Longitude (North)	Elevation (m)	Data Periods
1	Ames	42:02:00	93:48:00	335	1965–1989
2	Boone	42:03:00	93:53:00	317	1948–1989
3	Webster City	42:28:00	93:48:00	357	1993–1989
4	Fort Dodge	42:30:00	94:10:00	295	1948–1989
5	Humboldt	42:41:00	94:12:00	320	1956–1989
6	Clarion	42:44:00	93:44:00	360	1948–1989
7	Kanawha	42:56:00	93:48:00	363	1949–1989
8	Algona	43:04:00	94:18:00	375	1893–1989
9	Britt	43:05:00	93:48:00	369	1948–1989
10	Forest City	43:17:00	93:38:00	396	1948–1989
11	Titonka	43:17:00	93:59:00	357	1949–1989

Table 2. Univariate statistical results for the raingauge stations(excluding zero rainy days).

No.	Station Name	$\bar{m}$	σ	γ	K_n	CV
1	Ames	8.63	12.12	3.03	15.02	1.40
2	Boone	8.40	11.76	2.89	11.39	1.40
3	Webster City	8.21	11.57	3.64	22.90	1.41
4	Fort Dodge	8.17	11.93	3.38	17.26	1.46
5	Humboldt	8.70	12.72	5.02	48.75	1.46
6	Clarion	8.80	11.99	3.77	24.14	1.36
7	Kanawha	8.79	12.64	4.09	28.08	1.44
8	Algona	8.05	11.86	4.50	36.39	1.47
9	Britt	9.07	13.03	5.05	46.81	1.44
10	Forest City	9.69	13.79	4.51	35.11	1.42
11	Titonka	8.85	11.90	3.77	24.29	1.35

Note : The notation and units are : Mean ($\bar{m}$, mm/day), standard deviation (σ, mm/day), coefficient of skewness(γ), coefficient of Kurtosis(K_n), and coefficient of variation(CV).

of grids are 93:38:00 W, 94:18:00 W in longitude, 42:02:00 N, 43:17:00 N in latitude. Because the shape of Boone River basin is close to rectangular, all grid boxes within these boundary limits were used to compute MAP. The area within these boundaries is 7,700km^2 with 55.3km in longitudinal distance and 138.9km in latitudinal distance. Five grids in the x–direction and ten grids in the y–direction were used. For input data, 40 years of daily precipitation data from the USGS CD–ROM Disks, from 1949 to 1988, were used except for two stations. Table 1 shows the location of the stations and the data availability at each station.

4.2 Long–Term Rainfall Statistics

Precipitation is a random process that has a large time and space variability. Some long–term statistics are useful for describing the rainfall process in the study area. This statistical approach pays attention to the observations themselves rather than to the physical processes which produced them. The statistics are based on both including and excluding zero rainy days at each location for the periods of January 1, 1949 to December 13, 1988. Including zero rainy days, gave a maximum time average precipitation of 2.58mm/day at Stations 1 and 2, and a minimum one of 2.17mm/day at Station 7. The difference of estimated time average precipitation between these two rates results in an estimated difference of $3.271 \times 10^8 m^3$/year in water volume over the area of the Boone River basin.

Table 2 shows statistical results for the 40 year daily precipitation data excluding zero rainy days at each raingauge station on the Boone River basin. The high intensity rainfall for the daily average is recorded at the northeastern part of the basin, while the low intensity is recorded at the northwestern part and southern part of the basin. In this Table, the coefficient of skewness is a measure of the degree of asymmetry about the mean. Positive skewness in the range of 5 to 9 was observed at all 11 sites. The coefficient of variation is useful for comparing data from different sites. The spatial inhomogeneity of rainfall is apparent.

4.3 Optimal Location for MAP Estimation

Figure 3(a) shows the optimal location of raingauges as a function of number of stations under the assumption that estimated MAP from all existing 11 stations is the best one.

The Figure presents the quadratic error measure as a function of number of raingauges. It also serves as a comparison of the quadratic error corresponding to the optimal stations with that corresponding to the stations giving maximum quadratic error. It is obvious that seeking the optimal sites of raingauges is warranted given the large difference in quadratic error values (optimal is less than half in most cases). Figure 3(b) compares the results of global and forward searching methods. In both methods, the quadratic error(F_{obj}) shows a decreasing trend as the number of stations increases. It is interesting to observe the shape of the optimal raingauge network (GS method) as the number of raingauge stations increases. The single optimal raingauge is located in the center of the basin. As the number of stations increases, the shape of the network is changed to diagonal, that of a triangle and that of a rectangle covering mainly the western portion of the basin. The values of quadratic error converted to annual rainfall volume(m^3/year) are presented in Table 3. This table suggests the marginal gain of accuracy in MAP estimation between the two different searching methods. The percentage values in the table represent the ratio of quadratic error to annual average rainfall volume($7.00 \times 10^7 m^3$/year in the Boone River basin) obtained from the best observations.

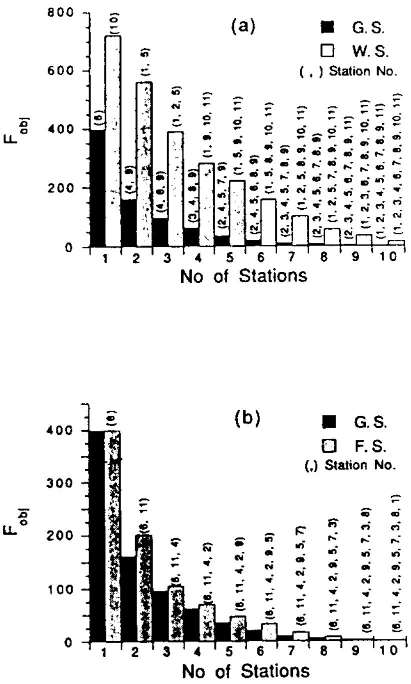

Fig. 3 Local optimal solutions according to the number of raingauges. G.S., F.S., and W.S. represent the global searching, forward searching, and worst station, respectively.

Table 3. The summation of quadratic error converted to annual rainfall volume(m^3/year). The percent value represents the ratio of quadratic error to annual average rainfall volume obtained from the best observation.

No. of Station	Quadratic Error		
	G.S.M.	F.S.M.	W.S.
1	2.16E7(30.86%)	2.16E7(30.86%)	3.89E7(55.57%)
2	8.64E6(12.34%)	1.08E7(15.42%)	3.02E7(43.14%)
3	5.18E6(7.40%)	5.67E6(8.10%)	2.09E7(29.86%)
4	3.45E6(4.93%)	3.78E6(5.40%)	1.51E7(21.57%)
5	1.92E6(2.74%)	2.54E6(3.63%)	1.19E7(17.00%)
6	1.12E6(1.60%)	1.77E6(2.53%)	8.42E6(12.03%)
7	5.18E5(0.74%)	9.18E5(1.31%)	5.40E6(7.71%)
8	3.45E5(0.49%)	4.48E5(0.64%)	3.02E6(4.31%)
9	1.30E5(0.19%)	1.30E5(0.19%)	1.86E6(2.66%)
10	4.97E4(0.07%)	5.07E4(0.07%)	8.42E5(1.20%)

Note : G.S.M. is the global searching method, F.S.M. is the forward searching method, and W.S. is the worst station given maximum object value.

It is obvious that MAPs computed using data from many randomly chosen stations are not always better than those computed using a few optimally selected stations. In terms of CPU time and for 40 years of daily data, the GS method takes 25.34 hours on an Apollo DN 10000 Supermini Computer, while the FS method takes only 0.81 hours.

4.4 Optimal Raingauge Network for Flow Prediction

The rainfall–runoff model composed of the modified Sacramento model and the conceptual kinematic stream routing model was used in an effort to determine the optimal number and location of raingauges for flow prediction. Precipitation data are one of the most important model inputs for accurate flow computations.

The NWS method and the arithmetic average method were used to compute MAP through the 40 year daily precipitation data record for Boone River. By comparing predicted flows at the basin outlet using the two different MAP computation methods, it was found that differences in estimated MAPs at a certain time step have a small effect on the flow estimates. When all 11 raingauges are used to compute MAPs throughout the 40 year test period, the cross correlation between observed and predicted discharges at the basin outlet is 0.868 when the NWS method is used, and it is 0.865 when the arithmetic average method is used. The main reasons for this small difference are that in this basin there is a fairly uniform coverage by raingauges, and that the terrain is flat.

Figure 4 presents the cross correlation coefficient (ρ_c) between daily observed and predicted flow computed for the 40–year test period as a function of the number of optimal raingauge stations obtained from Figure 3(a). The NWS method of MAP estimation was used. It can be seen from this Figure that two optimal stations (stations 4 and 9) give reasonable results. After 5 optimal stations, the cross correlation

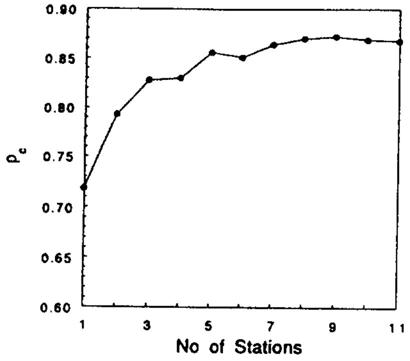

Fig. 4 The cross correlation between observed and predicted daily discharge as a function of number of raingauge stations with optimal locations.

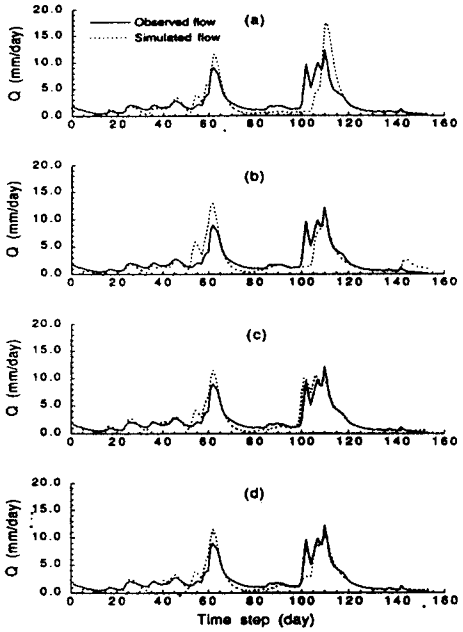

Fig. 5 The simulated discharge(mm/day) of different local optimal solutions from March 1, 1984 to July 31, 1984; (a) from single optimal station, (b) from two optimal stations, (c) from five optimal stations, (d) from ten optimal stations.

Table 4. Statistical results of flow prediction as the number of optimal raingauge sites changes.

No.	$\bar{m}_R$	ρ_R	$\bar{m}_p$	σ_p	ρ_c
1	0.053	0.784	0.419	1.075	0.718
2	0.082	0.752	0.554	1.234	0.793
3	0.063	0.645	0.536	1.147	0.828
4	0.029	0.605	0.501	1.060	0.830
5	0.050	0.573	0.522	1.098	0.856
6	0.053	0.566	0.525	1.058	0.851
7	0.023	0.527	0.496	1.013	0.864
8	0.023	0.512	0.495	0.999	0.870
9	0.020	0.503	0.492	0.984	0.872
10	0.020	0.510	0.492	0.979	0.869
11	0.020	0.511	0.492	0.978	0.868

Note : 1. Mean and standard deviation of observed flow is 0.472 and 1.007㎜/day, respectively.
2. $\bar{m}$ is mean with ㎜/day, σ is standard deviation with ㎜/day, and ρ_c is cross correlation between observed and predicted flows. Subscripts R and p represent residual and predicted flow, respectively.

coefficient almost converges to 0.86. This implies that 5 optimal locations are enough in the Boone River basin for accurate daily flow predictions. The two stations are located within the study basin and the rest of them are near its western boundary. The reason for selection of the three stations near the western boundary is that rain storms move from the West to the East (especially Southwest to Northeast) and the rainfall special pattern indicates high rainfall there. It may infer that these three stations near the boundary are highly affected for the estimate of MAP in the study area. The detailed statistical results are shown in Table 4. Figure 5 presents the observed and predicted discharges at the drainage basin outlet from estimated MAP computed using different optimal raingauge sites. The period is: March 1, 1984 to July 31, 1984. It is obvious that the estimated MAPs obtained from a single optimal location produce flows that overestimate the peak flows. It is clear, then, that the number of stations is much more important than the computation method of MAP in the Boone River basin as far as flow forecasting is concerned.

5. Conclusions

The weighted average method developed by the NWS was used to estimate MAP for use as input of hydrologic flow forecasting model. Two different searching methods were used to determine the number and location of the raingauge stations with data that produced small quadratic error measures in the estimates of MAP and in the predictions of flow. For this study, the 40-year daily precipitation data record available for the Boone River basin with outlet at Webster City, Iowa was used. Presented and discussed are results of this study.

(1) The data recorded at each raingauge station has an exponential frequency distribution. The maximum difference of time-averaged precipitation among stations in the Boone River basin was 0.41㎜/day.

(2) The optimal locations according to the number of stations were determined and are shown in Figure 3. This result suggests the priority of raingauge stations changing from manual data collection system to automatic real-time data collection system for the study area.

(3) MAPs computed using data from many randomly chosen stations are not always better than those computed using a few optimally selected stations (Figure 3).
(4) The forward-searching method saves much CPU time (32 times less than global-searching method in the particular example presented).
(5) For the long-term flow prediction, cross correlation between observed and predicted discharges is 0.86 if 5 raingauge stations (station numbers 2, 4, 5, 7, 9) are used to compute MAP. It would be 0.868 if all 11 stations were used.
(6) For the real-time flow forecasting, the arithmetic average method and the NWS method give very similar results for the Boone River basin.

Acknowledgement

The author would like to thank Dr. K.P. Georgakakos, Director, Hydrologic Research Center, San Diego, Ca. and Dr. R. Rajagopal, Professor, Dept. of Geography, The University of Iowa for many useful discussions during the course of this research.

References

1. Anderson, E. A. (1973) National Weather Service River Forecast System-Snow Accumulation and Ablation Model, NWS HYDRO-17, NOAA Technical Memorandum, Silver Spring, Md.
2. Anderson, E. A., and P. J. Neuman (1984) Inclusion of frozen ground effects in a flood forecasting model, Proceedings of the 5th northern research basins symposium, The role of snow and ice in northern basin hydrology, Vierumaki, Finland, Mar. 19-23, pp. 5.1-5.14.
3. Armstrong, B. L. (1978) Derivation of Initial Soil Moisture Accounting Parameters from Soil Properties for the National Weather Service River Forecast System, Rep. NWS HYDRO-37, NOAA, Silver Spring, Md.
4. Bae, D. H., and K. P. Georgakakos (1992) Hydrologic Modeling for Flow Forecasting and Climate Studies in Large Drainage Basins, IIHR Technical Report 360, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa., 252 pages.
5. Burnash, R. J. C., R. L. Ferral, and R. A. Mcguire (1973) A Generalized Streamflow Simulation System-Conceptual Modeling for Digital Computers, Technical Report, NWS, NOAA and State of Calif. Dept. of Water Resour., Joint Federal-State River Forecast Cent., Sacramento, Ca.
6. Georgakakos, K. P. (1986) A generalized stochastic hydrometeorological model for flood and flash-flood forecasting, 1, formulation, WRR, Vol. 22 No. 13, pp. 2083-2095.
7. Georgakakos, K. P., and R. L. Bras (1982a) A Precipitation Model and Its Use in Real-Time River Flow Forecasting, Report No. 286, Ralph M. Parsons Lab., Dept. of Civil Eng., M.I.T., Cambridge, Mass.
8. Georgakakos, K. P., and R. L. Bras (1982b) Real-time, statistically linearized, adaptive flood routing, WRR, Vol. 18 No. 3, pp. 513-524.
9. Kitanidis, P. K., and R. L. Bras (1980a) Real-time forecasting with a conceptual hydrologic model, 1, analysis of uncertainty, WRR, Vol. 16 No. 6, pp. 1025-1033.
10. Kitanidis, P. K., and R. L. Bras (1980b) Real-time forecasting with a conceptual hydrologic model, 2, applications and results, WRR, Vol. 16 No. 6, pp. 1034-1044.
11. Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus (1958) Hydrology for Engineers, McGraw-Hill Book Co., Inc., New York, NY.
12. NWS (1972) National Weather Service River Forecast System Forecast Procedures, NOAA Tech. Mem. NWS HYDRO-14, Silver Spring,

Md.

13. Peck, E. L. (1976) Catchment Modeling and Initial Parameter Estimation for the National Weather Service River Forecast System, Rep. NWS HYDRO-31, NOAA, Silver Spring, Md.
14. Rajagopal, R. (1983) Optimal sampling strategies for source identification in environmental episodes, Environmental Monitoring and Assessment, 4, pp. 1-14.
15. Rajagopal, R., and P. C. Li (1991) Comparison of two screening methods for the detection of VOCs in ground water, J. of Chemometrics, Vol. 5, pp. 321-331.
16. Reed, W. G., and J. B. Kincer (1917) The preparation of precipitation charts, Monthly Weather Review, 45, pp. 233-235.
17. Rodda, S. C., et al. (1969) Hydrologic Network Design-Needs, Problems and Approaches, Rep. 12, World Meteorology Organization, Geneva.
18. Singh, V. P., and P. K. Chowdhury (1986) Comparing some methods of estimating mean areal rainfall, Water Resources Bulletin, Vol. 22 No. 2, pp. 275-282.
19. Thiessen, A. H. (1911) Precipitation for large areas, Monthly Weather Review, 39, pp. 1082-1084.

〈접수 : 10월 31일〉