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HYDROLOGICAL MODELING OF THE UPPER CITARUM CATCHMENT, WEST JAVA

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The assessment of the complex hydrological characteristics in the upper Citarum catchment, West Java, is reported. The effects of population growth and land use changes on the state of water resources and its availability are also included. The validity of rainfall data of the hydrological system has been statistically checked for trends, independency, and mean and variance stability. The classic Thiessen Polygon method has been used in estimating the areal rainfall intensities over the catchment, while storm events with arbitrary return periods have been derived from the frequency analyses. The Pearson III distribution has been selected to simulate the rainfall-surface runoff relationship, to give the most reliable results. The flood analysis software HEC-1 has been employed to carry out the numerical simulations for a recorded flood event in 1994. The Cikapundung sub-catchment has been chosen, as a case study, for calibrating the hydrological simulations. The Soil Conservation Service method has been used in simulating and calibrating the runoff hydrograph, for various composite curve number values. Due to the complex features of the catchment, and due to lack of adequate land use data, extensive field measurement studies are needed to obtain sound predictions.

INTRODUCTION

The upper Citarum catchment in West Java, Indonesia, is located at 107^{o}15'E-107^{o}60'E and 6^{o}40'S-7^{o}15'S, with a surface area of about 4,800 km^2. The Citarum River flows from the Wayang Mountain to the Java Sea, with a length of about 240 km. In the upper Citarum catchment there are about 15 tributaries that flow into the Citarum River, and three large reservoirs linked in series. The Saguling Reservoir, the first in the series, lies about 10 km downstream of Bandung City at about 643 m above sea level, with a volume of 875x10^6 m^3, surface area of 48.7 km^2 and average depth of 18 m. The Cirata Reservoir is the second in the series, located at 220 m above sea level, with a volume of 2165x10^6 m^3, surface area of 62 km^2 and average depth of 35 m. The Jatiluhur Reservoir is the last in the series and the largest in the system, and is located at 15 km downstream of the Cirata Reservoir. The volume of the Jatiluhur Reservoir is 3000x10^6 m^3, with surface area of 83 km^2 and average depth of 36 m.

The purpose of the study is to assess the hydrological features of the upper Citarum catchment. The detailed validation process of rainfall records and their frequency analysis is presented. The Soil Conservation Service SCS method is employed in simulating the runoff hydrograph of the Citarum catchment. Finally, the HEC-1 software package is employed in predicting the runoff hydrograph in the Cikapundung sub-catchment, from which the application to the whole upper Citarum catchment is carried out.

LAND USE IMPACT ON UPPER CITARUM CATCHMENT

The Citarum River has a vital role in the economic development and prosperity of the people in West Java Province and Jakarta City. It has been exploited to support agriculture, fisheries, public water supply and industry, and generation of hydroelectric power. There are two protected forest areas in the upper Citarum catchment, which cover nearly 30% of its total area. The rest of the catchment is used for other activities, such as agriculture, residential and industrial activities. Bandung City, the capital of West Java Province, has a population of about 3.5 million and is surrounded by several sizeable towns, which form Greater Bandung. The annual growth rate of population for the District and Municipality of Bandung City was 1.16% during 1986-1995. In the past three decades, Bandung has experienced considerable rapid growth in industrial development and in urbanization. As such, large number of irrigated paddy fields and dry crops land in Bandung have been converted into housing complexes as well as business and industrial areas (Soestrisno, 1996).

The land use changes in the catchment have a detrimental impact on water quality and availability. The main source of pollution in the catchment is waste generated by more than 500 industries and a large population living in the vicinity of the Citarum River (Soestrisno, 1996). The quality of surface water is poorer during the dry season, as water levels subside, while waste from domestic and industrial sources discharged to the Citarum River and its tributaries remain virtually unchanged. With concurrent expansion of population and industrial activities, water quality in the river becomes even more deteriorated. Recent studies by Bukit (1998), Ilyas (2000) and Setiono et al. (2001) have confirmed the vulnerable situation of the upper Citarum catchment. Pollution incidents are regarded as a routine problem, particularly during the dry season, resulting in high mortality rates of ecosystems in the Saguling Reservoir, and to a lesser extent in the Cirata and Jatiluhur Reservoirs.

ANALYSIS OF RAINFALL DATA

The hydrological information of the upper Citarum catchment consists of a topographical map, rainfall data, meteorological data, and observed flow records taken from a single flood event. The topographical map is 1:50000 scale with contour interval of 25 m, drawn by the U.S. Army Map Service (Far East). The upper Citarum catchment consists of nine regions, within which 26 rainfall stations are spread. At each station, average daily and monthly rainfall data over a nine-year period (1986-1994) are recorded and analyzed.

The meteorological data required for the hydrology analysis of the Citarum catchment are also recorded monthly over a nine-year period, and are taken from the Geophysical and Meteorological Directorate (BMG) in Bandung. The data include temperature, humidity, wind speed, and percentage of sunshine. The full set of data used in the various hydrological analyses is given in detail in Yudianto (2002).

Validation of rainfall data

The spatial distribution of rainfall in the catchment is not uniform. Annual rainfall depth varies from 1966 mm up to 2600 mm. The wet season starts from November to April, and the wettest month could reach 300 mm. The remainder of the year is a dry or transition period. Annual records show that there are two peak events that occur during the rainy season. The first occurs in the March-April period, followed by a second peak in November-December. There is a period of declining rainfall between May and October where the rainfall remains relatively low. The average temperature in the upper Citarum catchment generally varies between 22°C and 24°C, and the relative humidity ranges from 25% up to 83% (Setiono et al., 2001, Soestrisno, 1996).

It should be mentioned that out of the 26 rainfall stations, 6 stations were found to have either data recorded over a short period (5 years or less), or have no data at all. It was therefore decided to exclude such data from the analysis. In general, the screening of recorded data against the following benchmarks is necessary before use in evaluating the hydrological components of the catchment; outliers, trends, mean and variance stability, and independency (Mays, 2001). Since monthly data are used in the analysis, rainfall data validation will be carried out on the same time scale. Daily maximum rainfall data for every month is also verified.

Outlier check

The outliers, which are the data points that depart significantly from the general trend, can seriously affect the magnitude of the resulting statistical parameters, especially for small samples. Using the generalized skew coefficient estimation (Kite, 1988), several outliers in the rainfall data at many rainfall stations were found. The detailed summary of rainfall stations having outliers is given in Yudianto (2002). Such extreme values had to be eliminated before proceeding to the next stage of data validation.

Trend check

The purpose of the trend check is to confirm whether the data is free of trends, i.e. no correlation should exist in either increment or decrement values. The Spearman's rank correlation coefficient R_{SP} is generally used for checking the availability of trends:

$$R_{SP} = 1 - \frac{6 \sum_{i=1}^{n} D_i^2}{n\ (n^2 - 1)} \qquad \text{With} \quad D_i = Kx_i - Ky_i \tag{1}$$

Where n = number of sample data, D_i = difference between rank of variable Kx_i (sorted ascending data) and Ky_i (sorted descending data). If two or more data are found to have the same values (ties), the rank of Kx_i is taken as average value. The statistical parameter, t_t, that is used follows the Student's t distribution, with degree of freedom n = n – 2:

$$t_t = R_{SP} \sqrt{\frac{n-2}{1-R_{SP}^2}} \tag{2}$$

The condition that satisfies no trend in a series of rainfall data is $t\{n, 2.5\ \%\} < t_t < t\{n, 97.5\ \%\}$. On that basis, several rainfall stations were found to have trends in their recorded data.

Mean and variance stability check

In order to check the stability of variance, the data is divided into two parts (sub-samples) of equal size. The Fisher distribution is used for presenting the ratio of the sample variance (Mays, 2001):

$$F_t = \frac{\sigma_1^2}{\sigma_2^2} = \frac{S_1^2}{S_2^2} \tag{3}$$

Where s and S = variance of population and sample respectively and indices 1 and 2 represent the sub-sample respectively. The condition that satisfies variance stability in a series of rainfall data is $F\{n_1, n_2, 2.5\%\} < F_t < F\{n_1, n_2, 97.5\%\}$, where $n_1 = n_1 - 1$ and $n_2 = n_2 - 1$ are the degrees of freedom of sub-samples 1 and 2 respectively, and F = Fisher distribution. Similarly, the data has stability of mean if the condition $t\{n, 2.5\%\} < t_t < F\{n, 97.5\%\}$ is satisfied. On that basis, several rainfall stations were found to have mean and variance instability. From the different analyses carried out on rainfall data, it was found that February and April have one error in the instability of mean values, while September and November have two errors in the instability of mean and variance trends. Due to the lack of adequate data, however, it was decided to include months with maximum two errors, such as February, April, September and November, in the rainfall analysis. Obviously, careful attention should be given to the use of such records in future applications.

Independency check

In addition to the above checks, all data must be specified as perfect random variables, i.e. no correlation should be found between any two sets of data. For this purpose, the Serial Correlation Method, with unit lag of calculation, has been used, which reveals the existence of close correlation between the data. The Serial Correlation coefficient, r_1 :

$$r_1 = \frac{\sum_{i=1}^{n-1} (x_i - \bar{x})\ (x_{i+1} - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{4}$$

Where n = number of sample data, x_i = data number i, $\bar{x}$ = mean of data sample. The following condition is necessary to satisfy independency in data: $\{-1, (-1 - 1.96\ (n-2)^{1/2} / (n-1)\} < r_1 < \{1, (-1 + 1.96\ (n-2)^{1/2} / (n-1)\}$. On this basis, it was found that only one rainfall station has dependency in their data.

To summarize the results of the above checks: 23 outliers were found in 11 rainfall stations and trends were identified in 11 months at 8 rainfall stations. Furthermore, mean instability in rainfall data was found in 11 months at 7 rainfall stations while variance instability was found in 22 months at 14 rainfall stations. Finally, dependency is found in July at one rainfall station (Yudianto, 2002).

Frequency analysis

The next stage after validating the rainfall data is the frequency analysis. The design events used for the frequency analysis are 10, 25, 50, and 100 years return periods. Among many probability distributions used are: the normal distribution, two-parameter log normal distribution, three-parameter log normal distribution, Pearson III distribution, log Pearson III distribution, and Gumbel type I distribution. After applying the Kolmogorov-Smirnov method for obtaining the goodness of fit of frequency distribution from the data sample, Gumbel type I distribution was found to give the best probability distribution, despite being relatively higher than those calculated from other distributions. On the other hand, it was found that the results from normal, two-parameter log normal, three-parameter log normal and Pearson III distributions give similar rainstorm values. As such, the Pearson III distribution has been chosen for the frequency analysis (Kite, 1988):

$$p(x) = \frac{1}{\alpha \ \Gamma(\beta)} \left(\frac{x-\gamma}{\alpha} \right)^{\beta - 1} \exp - \left(\frac{x-\gamma}{\alpha} \right) \tag{5}$$

Where $\Gamma(b)$ = the Gamma function. By applying the method of moments, the parameters α, β, and γ can be determined as:

$$\alpha = \frac{\sigma}{\sqrt{\beta}} \quad , \quad \beta = \left(\frac{2}{\gamma} \right)^2 \quad , \quad \gamma = \mu - \sigma \sqrt{\beta} \tag{6}$$

Where γ = skew coefficient, μ = sample mean, σ = standard deviation.

Calculation of areal rainfall intensities

The areal rainfall intensities over the catchment are calculated by applying the classic Thiessen polygon method (Shaw, 1983). This method was chosen because of the small difference found in the topographical levels over the catchment, and also for its relatively simplicity. However due to the limited rainfall stations, initial trials of this method revealed the existence of several sizeable zones, which would certainly yield inaccuracies in the calculations. Therefore, more interpolation between rainfall stations was necessary, which have resulted in denser polygons in the catchment. However, in order to ensure that all interpolated values lie within the limits of the observed values, the Inverse Square Distance method was applied. In total, 19 interpolated points were added to the existing rainfall stations.

Potential evapotranspiration

The potential evapotranspiration, PET, over the catchment was calculated by using the Penman equation. This equation estimates the maximum potential evaporation for given meteorological conditions (Chow, 1964):

$$PET = C \left[W \ R_n + (1 - W) \ f(u) \ (e_a - e_d) \right] \quad (mm/day) \tag{7}$$

Where C = weather condition correction factor, W = radiation effect factor, R_n = total radiation (mm/day), f(u) = wind effect factor, and e_a and e_d = actual and saturated air pressures (mbar) respectively. For given average monthly values of temperature, relative humidity, percentage of sunshine, and wind speed, PET can be computed from Equation (7). The only available set of data was located at the Bandung station, and hence it was applied to all calculations. In other words, the estimated PET was assumed to be spatially uniform over the entire catchment. With this approximation, for the available nine-year records, little difference was found in PET between dry (September) and wet (November, February, and April) seasons. The calculated monthly average potential evapotranspiration was found to vary between 3.84 and 4.98 mm (Yudianto, 2002).

Surface runoff hydrograph

The object of the rainfall-runoff analysis is to develop the runoff hydrograph, where the input to the system is the rainfall hyetograph, and the output is the runoff (discharge) hydrograph. The factors that decide the hydraulic features of a natural basin system include drainage area, channel slope and roughness, hydraulic storage and antecedent moisture conditions. One of the most widely used methods in analyzing rainfall-runoff, is the Unit Hydrograph. The Soil Conservation Service method (SCS) is a non-dimensional method used for calculating the unit hydrograph (Mays, 2001). It is based on the assumption that depth of excess precipitation or direct runoff, P_e, resulting from a rainstorm, is always less than or equal to that of precipitation P. The additional depth of water retained in the watershed F_a is less or equal to the potential maximum retention S. If it is assumed that I_a represents the initial infiltration index for which no runoff occurs, then the potential runoff is $(P - I_a)$. The SCS method assumes that the ratio of the actual to potential quantities is equal (Mays, 2001)

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{8}$$

As the continuity principle requires that $P = P_e + I_a + F_a$, Equation (8) reads:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{9}$$

This is the basic equation for computing the depth of excess rainfall or direct runoff from a storm by the SCS method. From the study of various watersheds, an empirical relation can be developed for the initial infiltration as $I_a = 0.2$ S. Hence P_e in Equation (8) becomes:

$$P_e = \frac{(P - 0.2\,S)^2}{P + 0.8S} \tag{10}$$

Empirical studies using the SCS method indicate that the potential maximum retention (storage) can be estimated by (Mays, 2001):

$$S = \frac{1000}{CN} - 10 \quad \text{With} \quad 0 < CN < 100 \tag{11}$$

Where CN = runoff curve number, which is a coefficient function of land use, antecedent soil moisture (AMC), and other factors affecting the runoff and water storage in the watershed. For impervious and water surfaces CN = 100 and for natural surfaces CN < 100. In general, antecedent moisture conditions (AMC) are grouped into three categories:

§ AMC-I for low moisture conditions.

§ AMC-II for average moisture conditions - normally used for annual flood estimation.

§ AMC-III for high moisture condition or for heavy rainfall preceding over few days.

For dry conditions (AMC-I) or wet conditions (AMC-III), equivalent curve number can be computed from (Mays, 2001):

$$CN(I) = \frac{4.2\ CN(II)}{10 - 0.058\,CN(II)} \quad \text{and} \quad CN(III) = \frac{23\ CN(II)}{10 - 0.13\,CN(II)} \tag{12}$$

Where CN(I), CN(II) and CN(III) correspond to antecedent soil moisture conditions AMC-I, AMC-II and AMC(III) respectively. According to the SCS method (Mays, 2001), soil is grouped into four classes according to their minimum infiltration rates. For a catchment made up of several soil types and land uses, a composite CN is normally used.

FLOW HYDROGRAPH IN THE CITARUM CATCHMENT

In order to attain realistic estimation of the runoff hydrograph for various flood events in the upper Citarum catchment, calibrating the parameters pertinent to the predictions is an essential step before use in real time situations. Ideally, the calibration should have been carried out for the whole upper Citarum catchment. In the absence of adequate information, however, the calibration has only been carried out on one representative sub-catchment within the upper Citarum, which is the Cikapundung sub-catchment.

The rainfall-runoff and the runoff hydrograph analyses are obtained by using the SCS Method. The routing calculations of the runoff hydrograph have been carried out using the HEC-1 flood analysis software package, developed by U.S. Army Corps of Engineers, 1998. The routing process in HEC-1 is based on the Muskingum-Cunge method, which is formulated from the coupling of the dynamic equations of motion, i.e. the continuity and momentum equations. Rough estimates for the parameters used in the HEC-1 model can be obtained: however, the model should be calibrated to observed flood data whenever possible. The parameter calibration option within the package has the capability to automatically determine a set of unit hydrograph and loss rate parameters that "best" reconstitute an observed runoff hydrograph for a catchment. The runoff parameters that can be determined in the calibration are the unit hydrograph parameters of SCS method. To help assess the results of the optimization, HEC-1 provides graphical and statistical comparisons of the observed and computed hydrograph results. From this, the user can then judge the accuracy of the optimization result and modify the parameters accordingly. The multiplan-multiflood simulation option allows a user to investigate a series of floods for a number of different characterizations (plans) of the catchment in a single computer run. The advantage of this option is that multiple storms and flood control projects can be simulated and compared efficiently.

Calibration process for the Cikapundung sub-catchment

As mentioned earlier, the calibration will be carried out on the Cikapundung sub-catchment before attempting to model the runoff hydrograph for the entire the upper Citarum catchment. This sub-catchment is located approximately in the central of West Java and has an area of 96.44 km^2 (Bukit, 1998). Only one flood event at Cikapundung River will be considered. It occurred at Gandok on 3-5 April 1994, which is located to the north of Bandung town, The rainfall data used for the calibration are taken from the existing rainfall stations and the additional interpolated stations, as given in Table 1.

In the procedure, the total area of the Cikapundung sub-catchment has been divided into six sub-areas where the outflow point is located at Gandok (where the flow observation is available). This is shown in Figure 1 along with the flow hydrograph computed from the 1994 flood event at Gandok.

Due to lack of land use information in the Cikapundung sub-catchment, the curve number CN had to be estimated. As such, the calibration has included several computational experiments for various CN values.

The flow chart of the calculation procedure using HEC-1 software and the computational results of the three calibration test runs are shown in Figure 2. As can be seen, the first calibration gives a good approximation despite the overestimation of the total storage (volume) of flow and the slightly longer time to attenuate the peak. The second calibration gives a very good comparison between the computed and observed flow storage despite the fact that the computed peak lies below the observed one. The third calibration again gives excellent results for the flow storage, but failed to predict the peak value realistically. In general, the computed predictions have similar profiles to the observed ones despite the fact that the computed peak value tends to be underestimated. These inaccuracies in the predictions are largely due to the crude estimation of the curve number. This calibration exercise, however, has confirmed the fact that good reliable data are essential to obtain sound computational results.

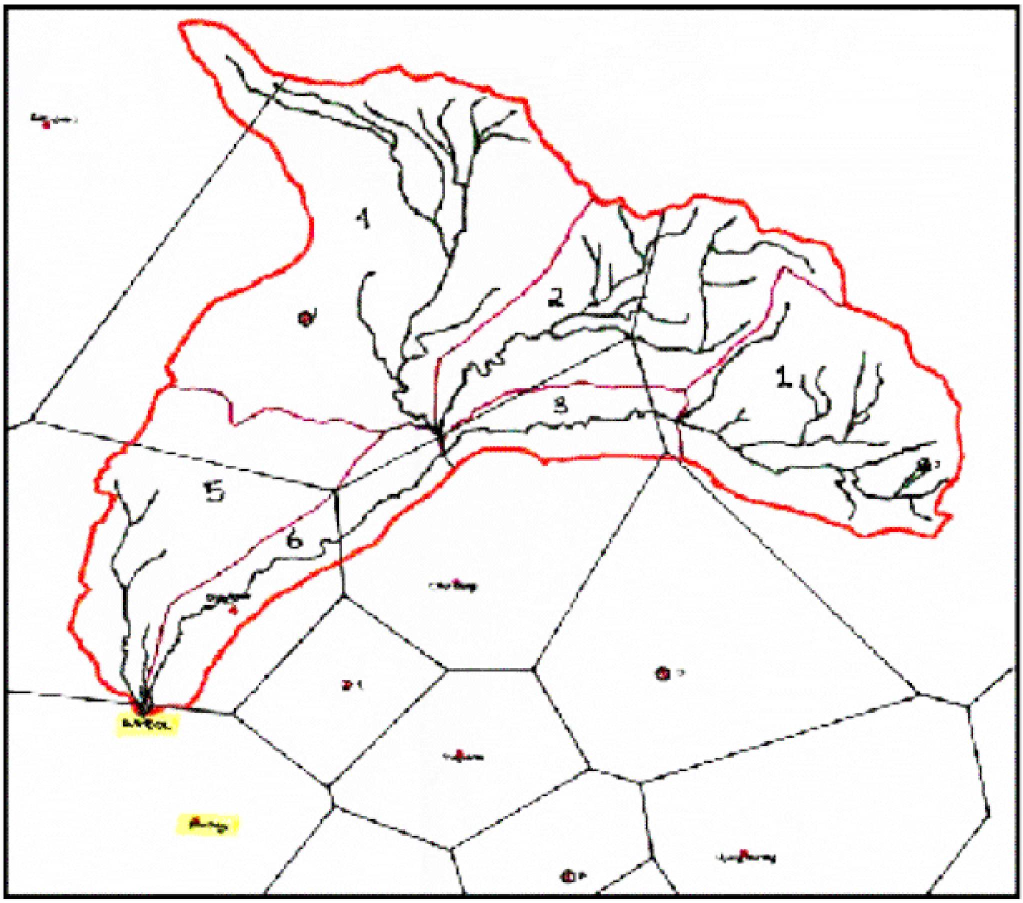
Table 1. Rainfall Data Used in the Calibration of Cikapundung Sub-catchment

Rainfall Station	**Station Condition**	**Rainfall (mm)**
Bandung	Existing	38.0
Sukawana	Existing	14.0
Dago Pakar	Existing	49.4
Ciharalang	Existing	43.3
Station 1	Interpolated	35.6
Station 2	Interpolated	27.1
Station 5	Interpolated	25.6

Application to the upper Citarum catchment

In order to apply HEC-1 software to the upper Citarum catchment (total area of 1569.36 km^2), it has to be divided into nine large sub-catchments. These are: Cikapundung, Cisariah, Citarik, Cikeruh, Ciganitri, Cisangkuy, Ciwidey, Cibeureum, and Cimahi sub-catchments. In the rainfall-runoff simulation, these nine large sub-catchments are divided into 51 sub-areas where some of the outflow points are located along the Citarum River, and the last outflow point is located in Nanjung (near to Saguling Reservoir) where the automatic water level recorder is available. The full set of rainfall data used in the calculations is given in Yudianto (2002).

On the basis of the data taken from a recent study in Indonesia, a detailed classification of land use changes in the catchment has been carried out using remote sensing studies from 1984 and 1996. The most significant change in land use is found to be the increase in the proportion of agriculture and settlement sectors. Due to the complexity of the hydrological characteristics over the catchment, and in the absence of adequate land use data, values for composite curve number, CN, ranging from 60



Sub-catchment	1	2	3	4	5	6
Area (km^2)	17.35	18.27	4.75	27.17	7.75	21.15

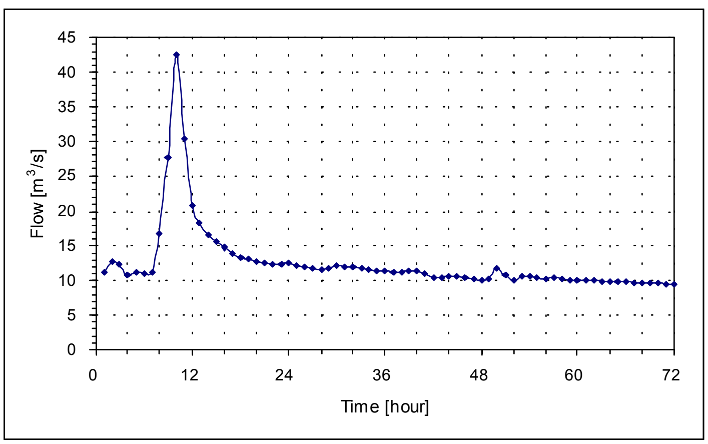


Figure 1. Hydrological properties of Cikapundung sub-catchment

to 80, have been used in the simulation process. Table 2 shows the estimated composite CN for the whole catchment based on land use changes (Yudianto, 2002).

The calculation procedure used in HEC-1 for the simulation of the hydrograph in the upper Citarum catchment is given in Figure 3. The summary of the computed flood hydrograph of the upper Citarum catchment at Nanjung station is shown Table 3. Due to the fact that HEC-1 software was developed for a single event analysis, and due to the spatial variations of rainfall over the catchment, the runoff simulation based on effective precipitation can be overestimated. However, verification of the computed runoff flow results against observations is essential before use in real life applications.

CONCLUSIONS AND RECOMMENDATIONS

Statistical methods are very important tools in validating recorded hydrological information within a river catchment. As a first step, rainfall data should be checked against the following benchmarks: outliers, trends, mean and variance stability, and independency. The next stage is the

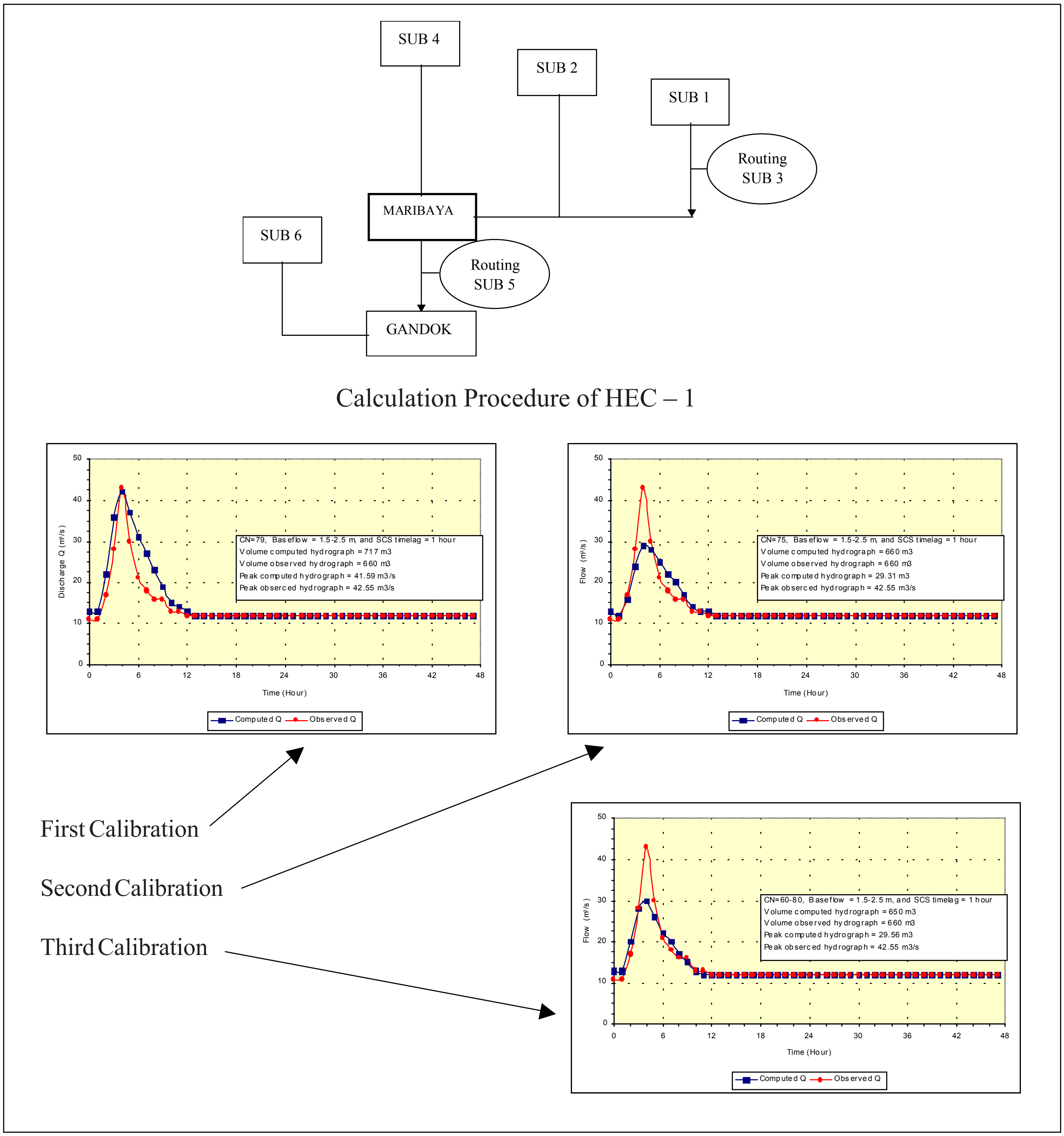


Figure 2. Calibration of Cikapundung Sub-catchment

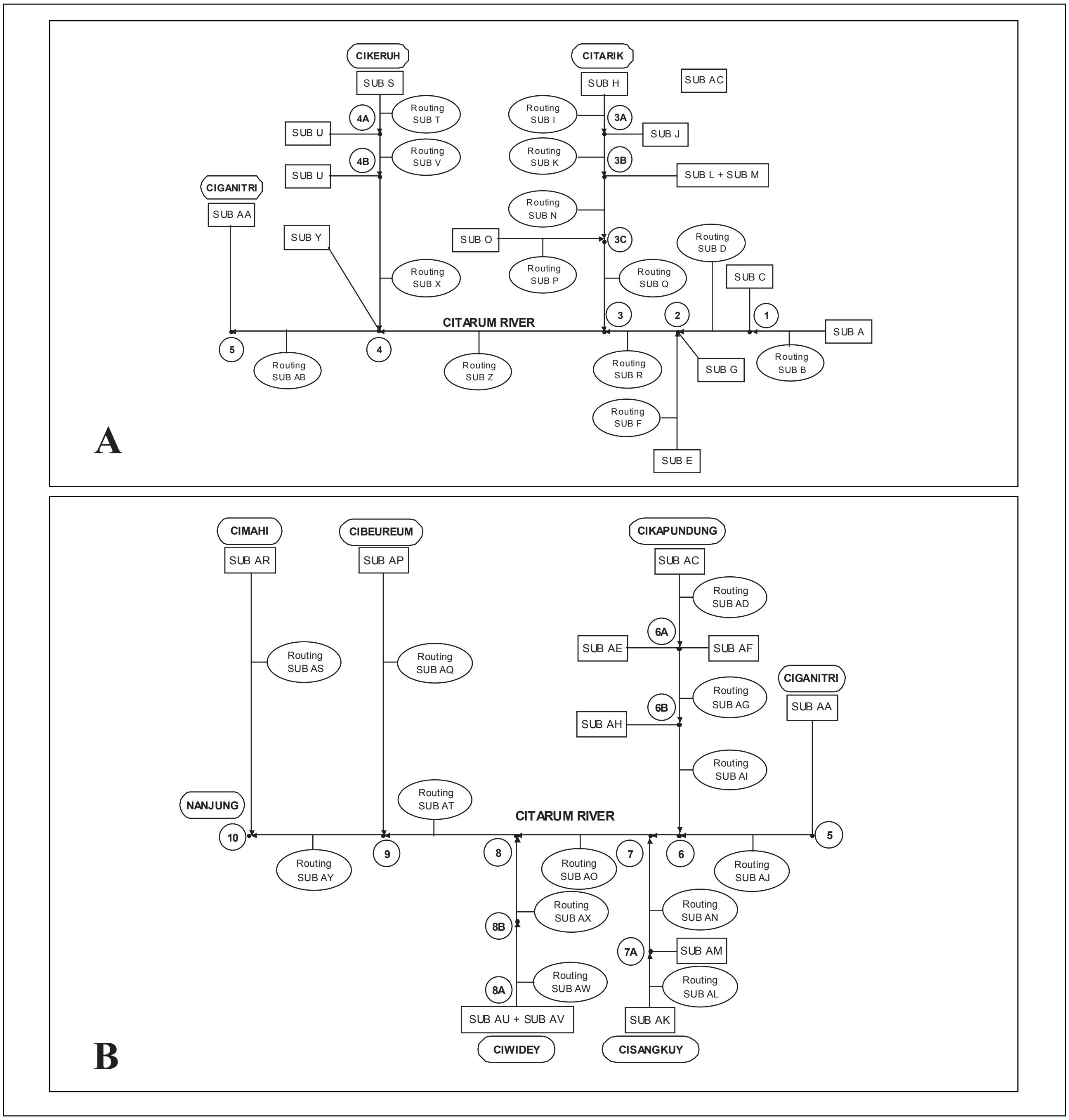


Figure 3. Calculation procedure of HEC-1 for the upper Citarum catchment. A and B are for L.H.S. and R.H.S. parts of the Citarum River

frequency analysis for various flood design events of arbitrary return periods. Establishing the level of confidence in records yields reliable rainfall–runoff analysis, from which the runoff hydrograph can be determined. The Soil Conservation Service method has been successfully employed in calculating the runoff hydrograph for river catchments. The HEC–1 software is a very reliable tool in predicting the design hydrograph for various design flood events. The magnitude of the curve number, which depends on detailed knowledge of the catchment, such as land use and topography, can have a significant effect on the hydrograph predictions.

While this study is considered to be the first step towards a more accurate simulation of the hydrological characteristics in the upper Citarum catchment, future studies are recommended which

Table 2. Estimation of Composite Curve Number CN for the Upper Citarum Catchment

No.	Land Use	Percentage of Land Use	Curve Number	Weighted CN
1	Forests	30	71.0	21.30
2	Agriculture	20	74.0	14.80
3	Settlement/Residential	34	73.5	24.99
4	Open Land	6	79.0	4.74
5	Grass Land	1	73.0	0.73
6	Water	7	98.0	6.86
7	Clouds	2	74.0	1.48
Composite Curve Number CN				74.90

Table 3. Computed Peak Flow Hydrograph for the Upper Citarum Catchment (m^3/s)

CN	February 1994				April 1994				September 1994				November 1994			
	Return Period (years)				Return Period (years)				Return Period (years)				Return Period (years)			
	10	25	50	100	10	25	50	100	10	25	50	100	10	25	50	100
60	634	956	1270	1610	790	1106	1406	1692	367	544	712	932	690	1015	1306	1612
65	959	1448	1842	2240	1197	1614	1976	2295	527	820	1081	1359	1054	1506	1859	2210
70	1417	2004	2456	2887	1687	2167	2567	2921	798	1195	1514	1843	1514	2052	2446	2829
75	1935	2598	3075	3644	2221	2756	3232	3715	1146	1631	2003	2375	2028	2628	3093	3612
80	2498	3358	4034	4676	2858	3595	4187	4717	1557	2120	2617	3127	2625	3445	4027	4607

should include:

- § Detailed field investigations for real-time rainfall data and flow records.
- § Information on land use, groundwater flow, geology, and industrial activities.
- § Concurrent studies should be carried out on water quality conditions and on their seasonal spatial changes within the catchment.

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