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DETERMINATION OF UNGAUGED CATCHMENT LOSSES RATE, CATCHMENT WETNESS INDEX AND BASEFLOW

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ABSTRACT

A single-event distributed model simulating inflow into the ungauged Batu Dam at Kuala Lumpur was formulated. This model is a one-dimensional finite element method that follows the procedure presented by Ross in [1]. With excess rainfall as input, the rainfall runoff simulation sub-model (as one of the sub-models in the developed Batu Reservoir Inflow Forecasting Model) was developed based on the one dimensional Saint-Venant equations with kinematic wave approximation and solved using the finite element standard Galerkin's residual method, and incorporating Manning's equation. The spurious oscillatory behaviour of the standard Galerkin's residual method can be suppressed by using a one minute time increment taking into cognizance the requirement of the Courant condition. The catchment losses rate concept developed in this study was dependent on catchment antecedent soil moisture conditions (catchment wetness index) and weighted average rainfall intensity. A catchment wetness index was formulated empirically based on the net total rainfall volume retained in the catchment accumulated over a five-day period prior to the simulated event (following the 5-day Antecedent Precipitation Index API5 concept). An empirical equation for computating baseflow volume for reservoir water level increment simulation was developed based on the five previous-days approach. The Catchment Losses Rate-Catchment Wetness Index-Weighted Average Rainfall Intensity (*LWRI*) curves were proposed for the study area, and seven curves were derived after model parameter calibration. Manning's coefficients used in model parameter calibration were also confirmed to be 0.400 and 0.040 for overland and channels respectively. The model was verified to simulate the reservoir water level increment accurately. This is shown by the very strong 0.9799 correlation coefficient, relatively small mean of absolute water level error that does not exceed 2.20 cm at 95% level of confidence from the single mean *t*-test, no significant differences in the means and variances from the paired *t*-test and the *F*-distribution variance ratio test respectively, and Theil's coefficient of 0.062 obtained.

Keywords: ungauged catchment, reservoir inflow, finite element, catchment wetness index, catchment losses rate, base flow.

INTRODUCTION

The advantage of a distributed model is that the model computes the flow rate and water level simultaneously, so that the model closely approximates the actual unsteady non-uniform nature of flow propagation in a stream channel. It is pertinent to propose a method of determining catchment losses rate, catchment antecedent soil moisture contents (catchment wetness index) and catchment baseflow volume for an ungauged rural catchment. The finite element method that is expounded here follows the procedure of [1] which is a one-dimensional kinematic-wave solution to the overland flow problem and thus not included herein. In a laboratory study by [2] with simulated uniform rainfall over the laboratory model catchment of the rainfall runoff over a leaky surface with various kinds of surface cover (sand, grass and plywood surface material to simulate different roughness) and where all portions of water are measured, the finite element solution of the kinematic-wave approach was proven to be exact and was also shown its inherent volume balance principle. The determination of runoff from the ungauged outlet of the catchment and into the reservoir in this case, can only be simulated with rainfall data and measured daily reservoir water levels at the dam.

Apart from this, the study has to look into (a) determining how the catchment losses rate can be represented and evaluated, and (b) determining the baseflow volume of flow. It was decided that a catchment wetness index is to be formulated based on the 5-day antecedent precipitation index concept for the former and that graphs relating catchment losses, wetness index and rainfall be developed for the latter purpose. The 5-day period follows that suggested in [3]. Another aspect that was needed to be checked was the Manning roughness numbers used. As it was the Manning numbers as most would know, were selected through recommendations from texts and there is no way to know if they had been suitably chosen.

CASE STUDY

The Batu Dam Catchment is located at about $3^{0}16'$-$3^{0}21'$ N latitude and $101^{0}40'$-$101^{0}43'$ E longitude in Peninsular Malaysia approximately 20 km north of the city of Kuala Lumpur (Figure-1). The 50.7 km^2 catchment is an undeveloped protected primary forested tropical catchment. The dam was planned for the Kuala Lumpur Flood Mitigation Project by the USBR (The United States Bureau of Reclamation) following the 1971 disastrous flood in Kuala Lumpur. The Batu Dam reservoir provides flood storage up to the 100-year frequency flood, and acts as a supply reservoir providing municipal and industrial water supply up to 25 million gallons per day to the surrounding areas [4]. The reservoir provides 4.88 million m^3 of exclusive flood control capacity at elevation 104.85

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m, and 7.4 million m^3 of surcharge capacity at the maximum elevation 107.86 m. The maximum capacity of the reservoir is about 36.62 million m^3 with the maximum surface area of approximately 2.5 km^2. About 95% of the catchment area (Figure-2) is classified as hilly with slopes varying from approximately 25 to 35%, and some even up to 40%. Batu River is the main river system in the catchment. It has a length of 11 km with a width of approximately 4 m upstream to 12 m downstream, and a depth of 3 m upstream to 1 m downstream. The slopes of the streambed vary from approximately 5% at the upstream to 1.5% at the downstream. Tua River and Bisul River are the other two smaller river systems in the catchment with lengths of 6.5 and 4.5 km respectively. The widths are approximately 4 m upstream to 7 m downstream for both rivers while the streambed slopes vary from approximately 3% upstream to 2% downstream. Gravels, cobbles and boulders cover all three streambeds.

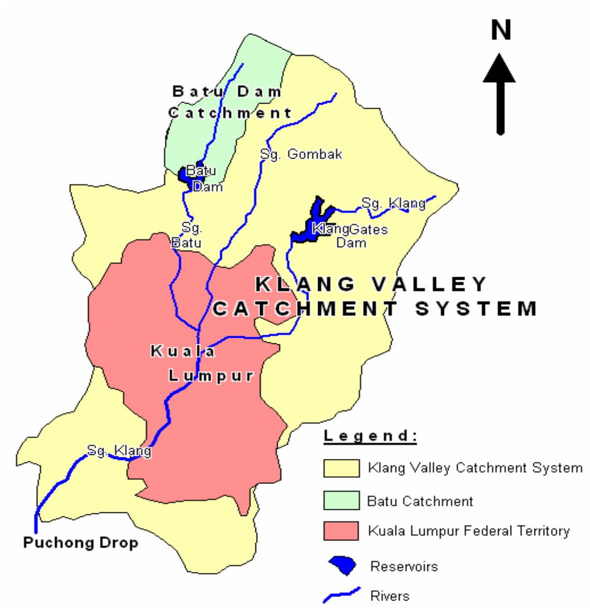

Figure-1. Location map of Batu dam catchment.

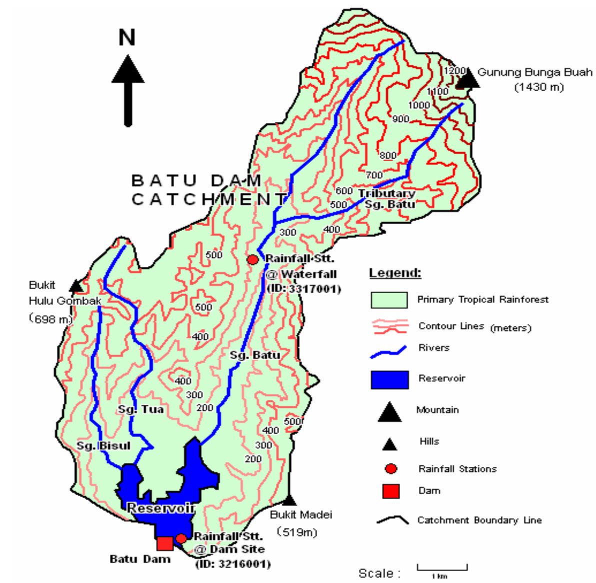

Figure-2. Topography map of Batu dam catchment.

The climate is humid tropical with average temperatures (between 32^0C and 23^0C) and high humidity (averaging about 80%) throughout the year. Rainfall occurs throughout the year with the wettest periods in October and November preceding the northeast monsoon season, and in April preceding the southwest monsoon season [5]. Intense thunderstorms are the predominant rainfall type with mean annual rainfall averaging about 3, 000 to 3, 500 mm. There are two telemetry rainfall stations: Dam Site Rainfall Station (Station ID: 3216001) is at the dam site while Waterfall Rainfall Station (Station ID: 3317001) is located mid-way of the catchment near a small waterfall. Data is recorded automatically at regular time intervals (usually at every 15 minutes). There is also a backup manually recorded rainfall station located at the dam site and a manual gauging station as well as a telemetric station (ID: 3216490) located at the reservoir for elevation gauging purposes. Data is taken daily at 8am.

FINITE ELEMENT CATCHMENT DELIMITATION

The criteria used in catchment delimitation mainly depend on the channel network system, the topography condition and the shape of the catchment. The respective surface roughness conditions of the overland and channels were assumed homogenous over the whole catchment. The catchment was delimitated into six sub-catchments, as shown in Figure-3. The first three sub-catchments, SC1, SC2 and SC3 consist of overland and channel flows, while the SC4, SC5 and SC6 consist of overland flow only. Since there is a 'Y' shape channel in the SC1, the sub-catchment was further sub-delimitated into three second level sub-catchments, namely SC1A, SC1B and SC1C.

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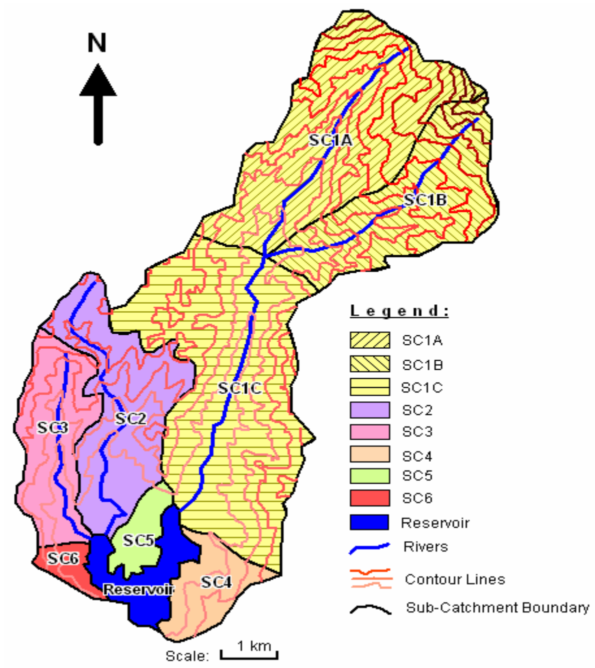

Figure-3. Sub-catchments delimitation of Batu dam catchment.

The sub-catchments and the second level sub-catchments of the Batu dam catchment were sub-delimitated into a number of overland strips, as shown in Figure-4. Some overland strips were even further sub-delimitated according to their shapes and slopes for use in finite element rainfall-runoff simulation purposes. The desktop mapping software package MapInfo Professional for Windows was selected for the development of Geographical Information Systems (GIS).

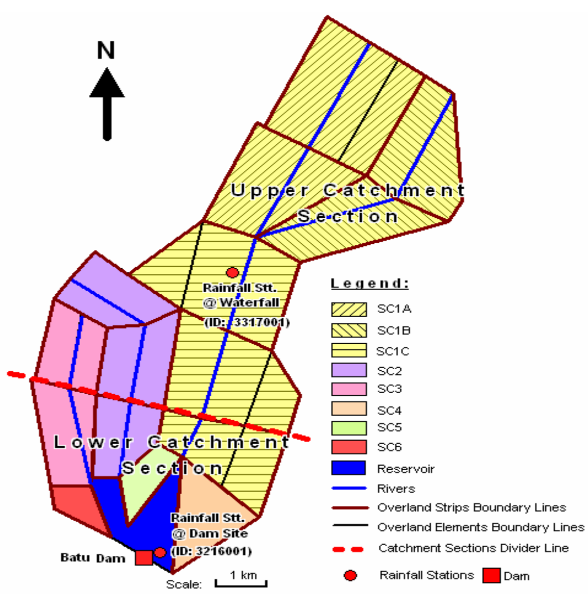

Figure-4. Finite element overland strips delimitation.

MODEL FORMULATION AND DEVELOPMENT

The model developed is a single event based model that can be used to forecast or simulate the reservoir water level increment after a rainfall event. For model parameter calibration and model verification purposes, each water level simulation period was set on a one-day basis since the reservoir water level of the catchment was taken every 24 hours at 8 am. Rainfall within a day (from 8 am to 8 am the next day) is defined as one rainfall event. Thus, each event day consists of only one rainfall event with one catchment losses rate.

Determination of model parameters

Since the main concern of a single-event based model is direct surface runoff, which occurs in a short period, the losses due to evaporation and evapotranspiration from the catchment land surface can be considered together with infiltration and surface detention as part of the catchment losses rate. However, the evaporation from the reservoir surface cannot be ignored, and were taken into consideration together with the other inflows (direct runoff, baseflow and direct rainfall flow into the reservoir) and outflows (seepage, domestic water supply and other outlet works discharges) of the reservoir to access the reservoir water level increment after a rainfall event. Excess rainfall can be computed from the rainfall data after determining the catchment losses rates due to infiltration, surface detention and interception.

The total areas of the upper section and the lower section of catchment by the Thiessen method are 36.3 and 14.4 km^2, respectively. Due to the spatial characteristics of the finite element method, the rainfall data used for the upper catchment area elements will be directly taken from the Waterfall Rainfall Station (Station ID: 3317001), while that for the lower catchment area elements will be directly taken from the Dam Site Rainfall Station (Station ID: 3216001). The catchment physical data such as finite element strip areas and dimensions were keyed-in into the MapInfo database and fixed throughout the whole calibration process, except for the surface roughness values for the overland and channel, which is one of the parameters needed to be calibrated.

To convert the telemetry point rainfall into the estimated areal average rainfall, a factor called Areal Reduction Factor [6] and [7] was introduced in this model. Two Areal Reduction Factor values were used in the development of the model: one for the Upper Catchment Section using catchment area 36.3 km^2; another one for the Lower Catchment Section using catchment area 28.8 km^2. The value of catchment area used for the Lower Catchment Section is double its actual area 14.4 km^2 since the rainfall station (Station ID: 3216001) is located at the boundary line of the lower section.

The concept resembling the simplest empirical Φ-Index method [8] was applied for infiltration rates estimation. The infiltration rate was taken to be constant throughout a rainfall event (soils in tropical forests are typically wet). Simplified further, the other losses such as the surface detention and interception were lumped together with the infiltration in the determination of the catchment losses rates. In this model, the catchment losses rate was assumed to be constant during a rainfall event and uniform over the whole catchment.

During calibration, a catchment losses rate was initially assumed, and the corresponding water level increment simulated was checked against the measured increment. The simulated catchment losses rates, grouped according to the weighted average rainfall intensities of the two rainfall stations, were then plotted against the antecedent soil moistures contents of the respective rainfall events to derive the required Catchment Losses Rate-Catchment Wetness Index-Weighted Average Rainfall Intensity (*LWRI* curves).

An empirical catchment wetness index was introduced to define the antecedent soil moistures contents of the rainfall events. The index is the ratio of the net total rainfall volume retained in the catchment of the event previous five days (the previous five consecutive days before the event) to the selected historical maximum (limited to the selected calibration cases). A five-day period was adopted following the 5-day Antecedent Precipitation Index (API5) approach adopted by [3]. The curves, after verifying, can be used for Catchment Losses Rate (*CLR*) determination in reservoir water level increment forecasting. The equations used to compute the Weighted Average Rainfall Intensity (*WARI*) and the Catchment Wetness Index (*CWI*) are expressed as in the groups of Equations 1 to 3 and Equations 4 to 6, respectively.

$$WARI = \frac{(WFARI \times 36.3) + (DamARI \times 14.4)}{50.7} \quad (1)$$

Where

$$WFARI = \frac{WFRF}{WFTRT} \quad (2)$$

$$DamARI = \frac{DamRF}{DamTRT} \quad (3)$$

Where

WARI	= Weighted Average Rainfall Intensity (mm/hr)
WFARI	= Average Rainfall Intensity (mm/hr) for Waterfall Rainfall Station
DamARI	= Average Rainfall Intensity (mm/hr) for Dam Site Rainfall Station
WFRF	= Rainfall (mm) for Waterfall Rainfall Station
WFTRT	= Total Raining Time (hr) for Waterfall Rainfall Station
DamRF	= Rainfall (mm) for Dam Site Rainfall Station
DamTRT	= Total Raining Time (hr) for Dam Site Rainfall Station

(36.3 is the Upper Catchment area; 14.4 is the Lower Catchment area; 50.7 is the total catchment area)

$$CWI = \frac{(WFNTRF \times 36.3 \times 10^3) + (DamNTRF \times 14.4 \times 10^3)}{HMax} \times 100 \quad (4)$$

Where

$$WFNTRF = \sum_{i-1}^{5} (WFRF_i \times \frac{CLR_i}{100}) \quad (5)$$

$$DamNTRF = \sum_{i-1}^{5} (DamRF_i \times \frac{CLR_i}{100}) \quad (6)$$

Where

CWI	= Catchment Wetness Index (%)
WFNTRF	= Net Total Rainfall (mm) for Waterfall Rainfall Station
DamNTRF	= Net Total Rainfall (mm) for Dam Site Rainfall Station
HMax	= Historical Maximum Net Total Rainfall (m^3)
WFRF	= Rainfall (mm) for Waterfall Rainfall Station
DamRF	= Rainfall (mm) for Dam Site Rainfall Station
CLR	= Catchment Losses Rate (%)
i	= Counter for Event Previous Days

Estimation of baseflow

In Batu Catchment, the baseflow volume is not available since it is an ungauged catchment. An equation based on the daily water balance approach was therefore proposed for computing the required baseflow volume. In order to compute the required baseflow volumes for reservoir water level increments simulation of an event, the net baseflow volume of the event previous day (called first event previous day) must first be computed using the proposed water balance equations as shown in Equations 7 and 8. It was assumed that only the direct runoff residuals (if any) from the four consecutive days previous to the event previous day would affect its water balance (based on the five previous day approach for estimating API5). Direct runoff residuals from much earlier days can be ignored since their effects are usually small. Direct runoff residuals are contributions from remaining continuing runoff from previous days' rainfalls. The daily water balance equation (in mixed units but can be expressed in common units in computation) can then be expressed as:

$$\Delta WL = \Pr eBF + \Pr eDRORES + \Pr eDRO + DRF - S - PN - Pi - RG - EV \quad (7)$$

After rearranging,

$$\Pr eBF = \Delta WL + S + PN + Pi + RG + EV - \Pr eDRORES - \Pr eDRO - DRF \quad (8)$$

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Where

Pre*BF* = Net baseflow volume of the event previous day
ΔWL = Variation in reservoir water level on the event previous day (equals to the final water level at 8am the next day minus the initial water level at 8am)
Pre*DRORES* = Direct runoff residuals (in volume basis) from the four consecutive days previous to, and simulated until the end of, the event previous day
Pre*DRO* = Direct runoff (in volume basis) of the event previous day
DRF = Direct rainfall onto the reservoir (on event previous day)
S = Seepage discharge through dam (on event previous day)
PN = Discharge by the Puncak Niaga for domestic water supply (on the event previous day)
Pi = Discharge to downstream areas through the 10-inch bypass pipe outlet work (on the event previous day)
RG = Discharge to downstream areas through the regulating gates outlet work (on the event previous day)
EV = Evaporation from the reservoir (on event previous day)

All the parameters used for computing the net baseflow volume of the event previous day (Pre*BF*) are known except for the direct runoff residuals from the four consecutive days previous to the event previous day (Pre*DRORES*) and the direct runoff of the event previous day (Pre*DRO*). Thus, in order to simulate these direct runoff residuals (if any) and the direct runoff of the event previous day itself (if any), a logical estimated catchment losses rate must be assigned to each day. An initial catchment losses rate of 85% (which is the estimated typical value for tropical forested catchment over a single tropical rainfall event) was assumed to be logical for this purpose. This estimated value, taken from the Hydrological Procedure [9], is considered a good estimate for an undeveloped forested rural catchment. Hence, any error in the simulated direct runoff residuals and direct runoff caused by misestimating of catchment losses rates is usually small. This computed net baseflow volume (Pre*BF*) is actually the original baseflow volume in the channels flows into the reservoir during the event previous day as if there were no rainfalls during the four consecutive days previous to the event previous day and the event previous day itself (since all the direct runoff residuals and direct runoff from these five days have been deducted).

This computed net baseflow volume of event previous day (Pre*BF*) is assumed to remain constant for the next 120 hours (five days). Thus, the baseflow volume for the first event day (*EventBF*) can then be computed by adding the total direct runoff residuals from the five consecutive days previous to, and simulated until the end of, the first event day (*EventDRORES*), to the computed net baseflow volume of the event previous day (Pre*BF*), as expressed in Equation (9):

$$EventBF = \mathrm{Pr}\, eBF + EventDRORES \tag{9}$$

Where

EventBF = Baseflow volume of the first event day
Pre*BF* = Net baseflow volume of the event previous day
EventDRORES = Total direct runoff residuals (in volume basis) from the five consecutive days previous to, and simulated until the end of, the first event day

No baseflow volumes will be computed for the simulation period after the first 24 hours. The computed baseflow volume for the first 24 hours (*EventBF* in Equation 9) will be assumed valid, and can be used for the next the entire maximum 120 hours simulation period. Using this baseflow volume for the rest of the simulation period is conservative since it is always bigger than those volumes of the simulation period after the first 24 hours, due to smaller direct runoff residual volumes during the later stages. Therefore, the simulation period of each water level can be of any length of time as long as the total simulation period is not more than 120 hours. For water level simulation period other than 24 hours, the baseflow volume can be prorated.

Simulation of water level

For water level forecasting purposes, the simulation can be started from any time as long as the initial reservoir water level is known. The time increment value used for simulation in the model was fixed to one minute. The spurious oscillatory behaviour of the standard Galerkin's residual method can be suppressed by using a one minute time increment taking into consideration the Courant condition. The direct runoff hydrograph (which cannot be verified in view of the fact that the catchment is ungauged) of the whole catchment and the total direct runoff volume of each sub-catchment can be displayed in the model.

Before simulating the reservoir water level increment of the selected water level simulation period, the starting and ending times of each simulation period must be defined. A water level simulation period is defined as the time desired and used for a reservoir water level increment simulation. Each simulation period can be of different time span. After defining the simulation periods for reservoir water level increments simulation, the water level increments of each simulation period can be simulated based on the daily water balance approach.

As the first step to simulate the reservoir water level increment of a simulation period, where the initial reservoir water level is known, the net inflow volume into the reservoir for that period is computed:

$$NIV = DRO + BF - (PN + Pi + RG) - S \qquad (10)$$

Where

NIV = Net Inflow Volume into the reservoir (m^3)
DRO = Simulated Direct Runoff volume into the reservoir (m^3)
BF = Computed Baseflow volume into the reservoir (m^3)
PN = Discharge by Puncak Niaga for domestic water supply (m^3)
Pi = Discharge to downstream through the10-inch bypass pipe outlet work (m^3)
RG = Discharge to downstream through the regulating gates outlet work (m^3)
S = Seepage discharge through the dam (m^3) measured at rate of 2.6 l/s

Before converting the computed net inflow volume into the reservoir to a water level basis, the intermediate reservoir water level must first be computed:

$$INTWL = IWL - EV + DRF \qquad (11)$$

Where

INTWL = Intermediate reservoir water level (m)
IWL = Initial reservoir water level (m)
EV = Evaporation from the reservoir (m)
DRF = Direct rainfall onto the reservoir (m)

The computed intermediate reservoir water level (*INTWL*) can then be used to simulate the intermediate reservoir capacity using the Batu Dam Reservoir Elevation-Capacity Curve developed during the construction of the Batu Dam (Figure-5). The computed net inflow volume into the reservoir (*NIV*) will be added to this simulated intermediate reservoir capacity to compute the final reservoir capacity, which will be used to simulate the final reservoir water level.

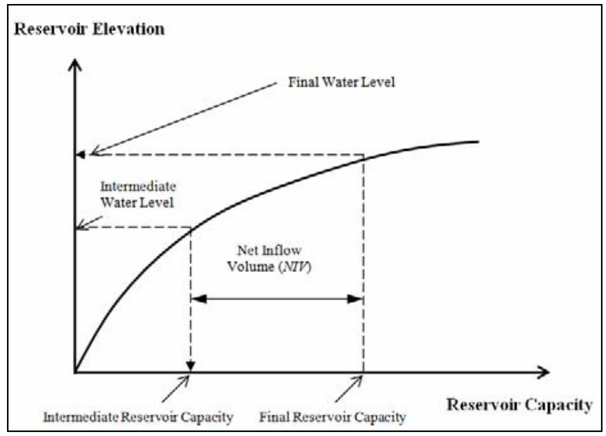

Figure-5. Batu dam reservoir elevation-capacity curve.

The Batu Reservoir Inflow Forecasting Model was programmed in the Map Basic conventional programming language, and runs incorporation with the MapInfo professional package. The main menu of the Batu Reservoir Inflow Forecasting Model is shown in Figure-6. The model consists of several sub-models that include excess rainfall simulation sub-model, finite element rainfall-runoff sub-model, Baseflow calculation sub-model, and reservoir water level simulation sub-model.

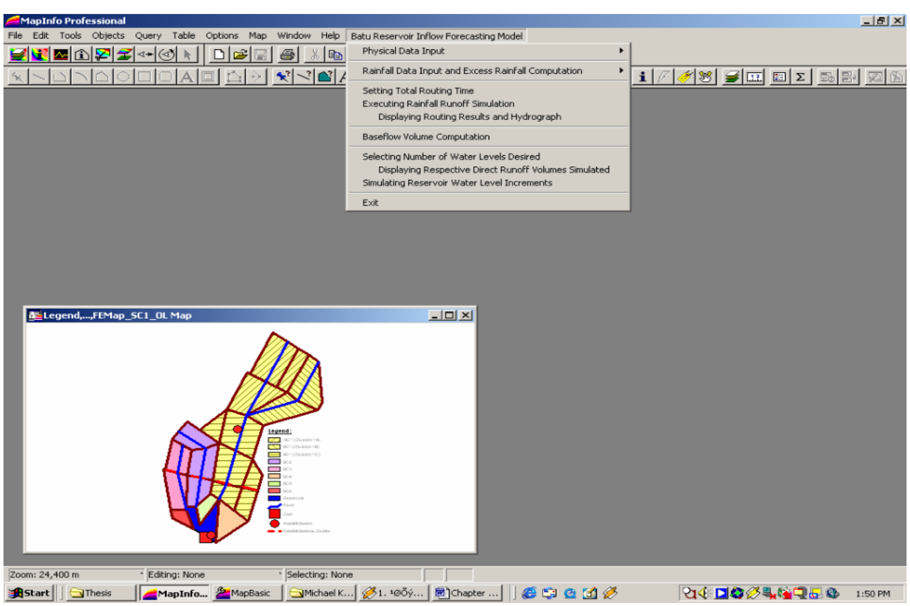

Figure-6. Display of the main menu for batu reservoir inflow forecasting model.

RESULTS AND DISCUSSIONS

Selection of rainfall events

One hundred twenty cases (Table-1) from thirteen years of historical data (from year 1989 to 2001) were selected for model parameter calibration and model verification purposes. The selected cases were then separated into 13 groups according to their weighted average rainfall intensities. Then, from each group (except for the Groups A, C, I, K, L and M, which have fewer cases each), about 25% of the cases were randomly selected and used for model verification purposes; while the remained cases (75%) were used for model parameter calibration purposes.

Table-1. Grouping of the selected rainfall event cases.

Group	**Weighted average rainfall intensities** (mm/hr)**, and their respective ranges**	**Total number of selected cases**	**Cases for model parameter calibration purposes**	**Cases for model verification purposes**
A	2.5 (1.25-3.75)	1	-	-
B	5.0 (3.75-6.25)	9	7	2
C	7.5 (6.25-8.75)	2	-	-
D	10.0 (8.75-11.25)	28	20	8
E	12.5 (11.25-13.75)	22	16	6
F	15.0 (13.75-16.25)	22	16	6
G	17.5 (16.25-18.75)	14	10	4
H	20.0 (18.75-21.25)	9	7	2
I	22.5 (21.25-23.75)	2	-	-
J	25.0 (23.75-26.25)	6	4	2
K	27.5 (26.25-28.75)	2	-	-
L	30.0 (28.75-31.25)	2	-	-
M	37.5 (36.25-38.75)	1	-	-
Total Cases:		120 (110)	80	30

Model parameter calibration

Under model parameter calibration, the parameters to be calibrated or determined are CLR to be incorporated into *LWRI* Curves, and the Manning's Coefficients for the channel and overland.

Determination of *CLR*

The purpose of model parameter calibration is to obtain a unique parameter set that gives the best possible fit between the simulated and the measured values. In this model, the simple trial and error approach was chosen for model parameter calibration purpose since the catchment losses rate is the only parameter to be calibrated. The other two unknown parameters, catchment wetness index and baseflow, can be computed accurately based on the explanations given earlier. The calibration of catchment losses rate for a selected case was carried out for an assumed initial value for each simulation. Simulations were repeated with adjusted values until an agreement between the simulated water level increment and its corresponding measured value was reached. Upon completion of catchment losses rates calibrations, their corresponding values of catchment wetness index were calculated using Equations (4), (5) and (6).

The case selected for computing the historical maximum (*HMax*) in the computation of catchment wetness index is Case 110696 (refer to maximum rainfall occurred on 11 June 1996 till the time of this study). After calibration, this selected historical maximum was programmed into the model as the standard maximum net total rainfall volume remains in the catchment. These values of catchment losses rate and catchment wetness index together with their respective weighed average rainfall intensities, were next used to plot the *LWRI* curves. The cases from the same weighted average rainfall intensity group were finally used to plot the respective *LWRI* curve. In view of the limited cases available, and from a visual inspection of each plot data set, a straight-line curve was chosen to approximate the expected hyperbolic curve. Figure-7 shows the set of *LWRI* curves for the seven groups. These *LWRI* curves were programmed into the model for model verification and future forecasting use. Interpolation between curves was also implemented.

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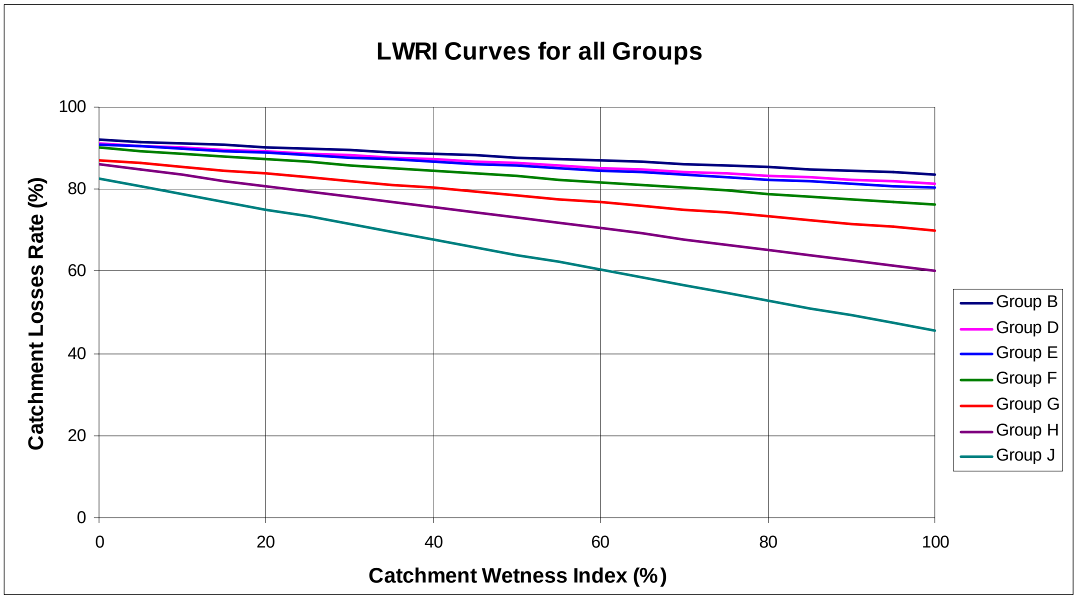

Figure-7. *LWRI* curves for all groups.

Determination of manning's coefficients

In order to verify the correctness of the Manning's coefficients used in *CLR* determination above, which were 0.400 for overland and 0.040 for channels, 20 of the 80 cases in column 4 of Table-1 were randomly selected. The reservoir water level increments of the selected cases were checked against the corresponding measured values. If both the simulated and measured increments tally, then it can be concluded that their direct runoff volumes are similar. This does not only indicate that the Manning's coefficients are correct, but also confirms that the calibrated catchment losses rates are appropriate. These coefficients, 0.400 for overland and 0.040 for channels, were as recommended in [10] and [11], respectively. Results in Figure-8 shows that the simulated water level increments of all the case are reasonable.

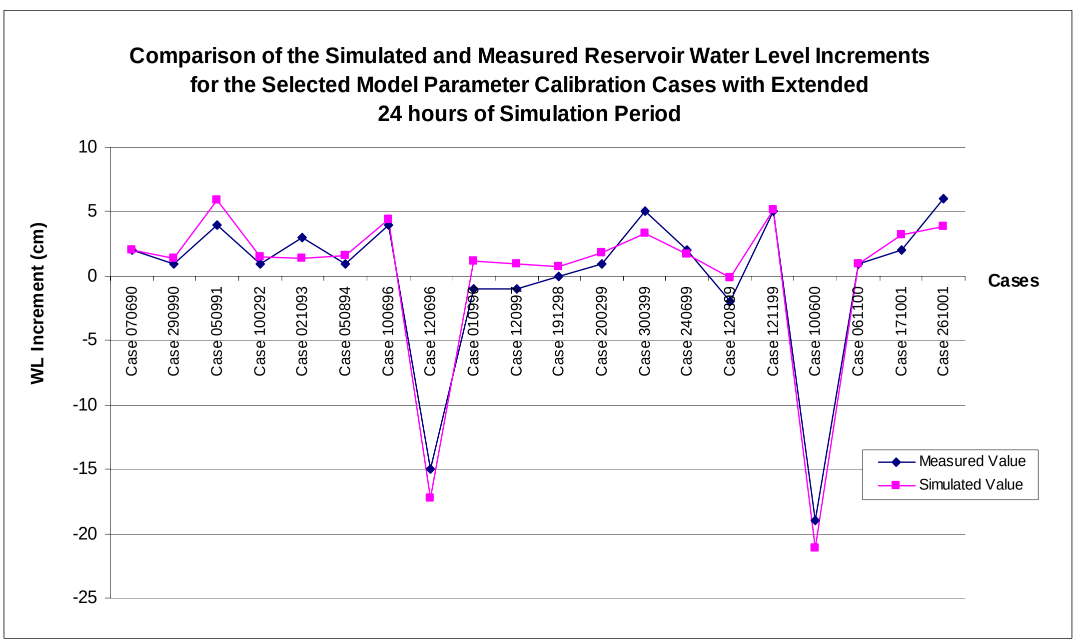

Figure-8. Comparison of the simulated and measured reservoir water level increments for the selected 20 cases for verifying the Manning's coefficients used.

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Batu reservoir inflow forecasting model verification

After calibrating the parameters, the verification process was conducted by comparing the simulated reservoir water level increments with the corresponding measured values for the 30 cases in Table-1 (column 5) which were kept aside for verification purposes. Figure-9 shows the simulated results and the corresponding measured values. From the graph, it can be seen that both results are comparable, confirming the adequacy of the calibrated parameters to the real catchment response.

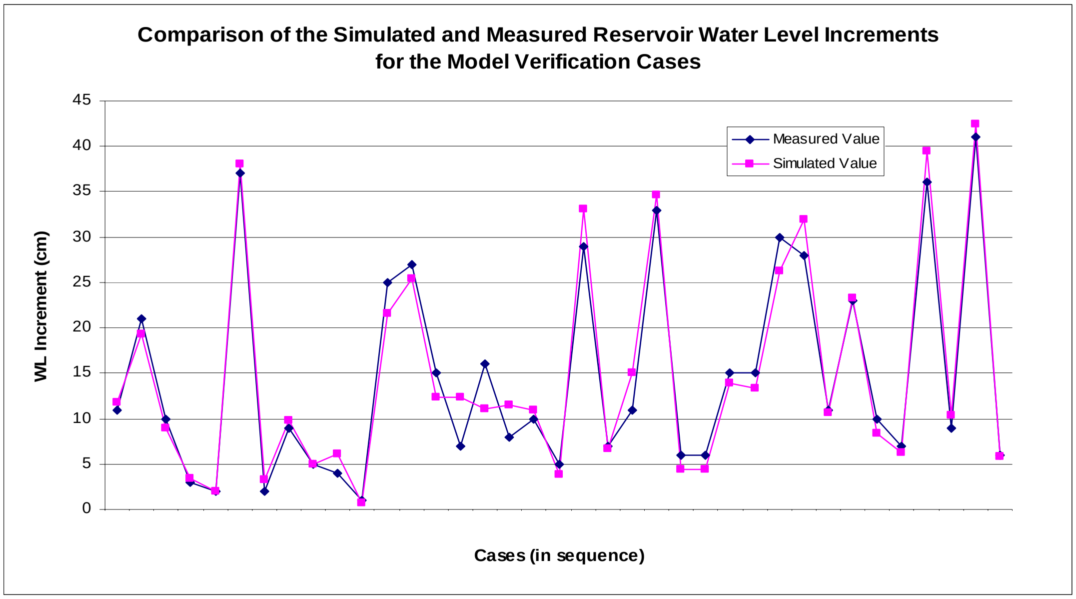

Figure-9. Comparison of the simulated and measured reservoir water level increments for the batu reservoir inflow forecasting model verification cases.

To further strengthen this confirmation, statistical tests need to be carried out. The coefficient of correlation was found to be 0.96. From paired *t*-test, it was found that the null hypothesis, with the acceptation region -2.029 < t_o < 2.029, cannot be rejected at the 95% level of significance, since the test statistic t_o = 0.463, falls into its acceptation region. There is thus insufficient evidence to indicate the two populations do not have significantly different means.

From the single mean *t*-test, it was found that the null hypothesis, with the rejection region $t_o \leq$ -1.689, was first rejected at the 95% level of significance for μ_o = 2.20 (The respective test statistic of the test is -1.696). Hence, it can be stated that there is insufficient evidence to indicate that the mean of the absolute error between the measured and simulated values equals or exceeds 2.20 cm.

Furthermore, the *F*-distribution variance ratio test was also carried out to test the compatibility of variances between the simulated increment (σ_1^2) and measured increment (σ_2^2) populations of the model verification cases. The two-tailed null and alternative hypotheses formulated for the two populations are H_0: $\sigma_1^2 = \sigma_2^2$ and H_1: $\sigma_1^2 \neq \sigma_2^2$, respectively, with the acceptance region of the null hypothesis was found to be 0.51 < f_o < 1.96. The calculated variances for the simulated increment and measured increment were 135.298 and 125.908, respectively. The test statistic was $f_o = S_1^2 / S_2^2$ = 1.075, which falls into the acceptance region of the null hypothesis. Therefore, the null hypothesis cannot be rejected at the 95% level of significance, and there is no strong evidence to support that the variances of the two populations are different.

Model evaluation

Model evaluation involves model testing, and comparison of the objective model with other models or methods. The performance of model is tested to evaluate how adequate the model is in representing the real behavior of the catchment. Herein, the model was tested using the well-established Theil's technique [12]. The values of Theil's coefficient vary between zero and one, $0 \leq U \leq 1$. The model is considered to be perfect in its application if the Theil's coefficient is zero. Contrary, if the coefficient is equal to one, then it can be concluded that the model is totally unreliable. In order to test the performance of the model developed, the simulated and measured reservoir water level increments of the model verification cases were used to calculate the Theil's coefficient, *U*. It was found that the calculated Theil's coefficient was 0.062. This small value of *U* indicates that the model can perform well, and gives reliable results.

CONCLUSIONS

A single-event distributed model simulating inflow into the Batu Reservoir in Kuala Lumpur with kinematic wave approximation, incorporating Manning's equation, for the one dimensional direct runoff in a GIS environment was successfully developed. The Catchment Losses Rate-Catchment Wetness Index-Weighted Average Rainfall Intensity (*LWRI*) curves were successfully generated through model parameter calibration process, and programmed into the model for verification and future forecasting purposes.

Verification of model shows that the model is able to simulate results with mean absolute error that does not exceed 2.20 cm at 95% level of confidence, and having very strong correlation (0.96) with measured values. It was also supported by the statistical paired *t*-test and *F*-distribution variance ratio test done. Evaluation of the model shows the model is able to forecast good results. Theil's coefficient was evaluated to be 0.062 for the model. Thus, the empirically formulated catchment wetness index computation method similar to the API5 approach for the ungauged catchment is confirmed to be adequate in representing the antecedent soil moisture contents of catchment.

Finally, the concept of developing the *LWRI* curves for determining the catchment losses rate is reasonable and acceptable. An empirical baseflow volume computation method was developed for use in the model, and was proven appropriate for use. The Manning's coefficients for the overland and the channels of the catchment have been determined to be 0.400 and 0.040, respectively.

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