Memoirs of the Faculty of Engineering, Kyushu University, Vol. 57, No. 3, September 1997

Interactive User Interface for Rainfall-Runoff Analysis by Tank Model

by

Tarek MERABTENE*, Kenji JINNO**,

Akira KAWAMURA*** and Takeshi MATSUNAGA****

(Received July 7, 1997)

Abstract

In this paper an interactive user interface for calibration of the tank model is presented. The system has been developed to assist hydrologists and potential users to optimize the model for their intended objective. The user friendly system permits the selection of several tank configurations, ranging from a very simple one (1 tank with 2 parameters) to a very complicated one (4 tanks with 40 parameters). During the trial and error procedure different periods of observed data can be selected for calibration and validation of the selected model. To assess the model parameters reliability an integrated data base manager provides a number of statistical criteria for each trial, in addition to a graphic display of the simulated results. The data base will serve as a decision support for further use of the model and future development of an expert system for the tank model calibration. The developed model was applied to the hydrologic characterization of five catchments in Fukuoka City and to Kuji river basin in Ibaragi prefecture, Japan.

Keywords : Rainfall-runoff models, Tank model, Interactive user interface, Database, Extended Kalman filter

1. Introduction

Over the past three decades, considerable research in hydrology has concentrated on development of mathematical rainfall-runoff models for better understanding of the catchment response complexity. In practice, beside the choice of the model, the most important is its calibration using either a manual or automatic process. Optimization algorithms for an automatic estimation of model parameters of conceptual rainfall runoff models have attracted much attention, and several difficulties have been reported[1,2,3,4,5,]. Almost all optimization methods developed to date, with their different degree of robustness and/or complexity,

---

* Graduate Student, Department of Civil Engineering

** Professor, Department of Civil Engineering

*** Associate Professor, Department of Civil Engineering

**** Research Scientist, Japan Atomic Energy Research Institute

reach to the same conclusion, that is, the inability to obtain a unique and global optimum of the model parameters. Johston and Pilgrim[2] concluded at the end of their work that, "A true optimum set of values was not found in over 2 years of full-time work concentrated on one watershed". Gan and Biftu[4] believe that obtaining a set of global optimum parameters through any automatic calibration procedure is a remote possibility. Thus, to alleviate the problems associated with the calibration of the tank model by trial and error procedure, an interactive user interface (IUI) has been developed in a manner to increase the practical utility of the model to planners and policy makers. The framework of the system consists of three main modules: (1) the mathematical algorithm of the tank model, (2) the selection of the structure of the tank model and its parameter identification, and (3) a data base manager of two sub-modules: one for the available observed data and one for the different sets of model parameter selected during calibration. The developed system was applied to the characterization of five catchments in Fukuoka City and to Kuji river basin in Ibaragi prefecture, Japan.

2. Tank model

The developed IUI provides two versions of the tank model to simulate the runoff process: a 'fixed parameter tank model' where the parameters remain constant at each time step and an 'adaptive parameter tank model' where the parameters are updated by Kalman filter.

2.1 Fixed parameter tank model

The tank model has been introduced by Sugawara[6,7] to estimate the flow of several rivers in Japan. It is a conceptual rainfall-runoff model characterized by one or several interconnected storage units (i.e., tank). Tanks are equipped with side outlets to simulate the runoff components and bottom outlets for the infiltration process. The top tank, generally, has two side outlets, while the other tanks are equipped with one side outlet only, see **Fig. 1**.

The runoff components from the outlets are usually expressed as a linear relation of the storage amount, i.e., water level in tank. Whenever a linear relation does not generate satisfactory result a simple square relation can also be used[8,9]:

$$Q_{i,k} = A_{i,k}(H_i - C_{i,k})^{\gamma} U(H_i - C_{i,k}) \tag{1}$$

the unit step function U(•) is defined as:

$$U(H_i - C_{i,k}) = 1 \ \ if \ \ H_i > C_{i,k}$$
$$U(H_i - C_{i,k}) = 0 \ \ if \ \ H_i > C_{i,k}$$

the infiltration to the bottom tank is expressed by:

$$I_i = B_i H_i \tag{2}$$

where $\gamma = 1$ for a linear equation, $Q_{i,k}$ is the simulated runoff components from hole k of tank i, usually expressed as unit of length/time, I_i the infiltration from tank i to the next lower tank $i+1$ (unit of length/time), H_i the water storage level in tank i (unit of length), $A_{i,k}$, B_i (unit of 1/time) control the flow rates, and $C_{i,k}$ (units of length) is the threshold of the hole k in tank i, i ($i=1, \ldots, N$) is the number of tank, and k ($k=1, \ldots, K$) the number of side outlets in tank i, in the developed system N and K equal a maximum of 4 (i.e., $N=4$ tanks with $K=4$ holes in each tank), see **Fig. 1**. $A_{i,k}$, B_i and $C_{i,k}$ are the unknown parameters of the tank model to be optimized. In a fixed parameter tank model the parameters $A_{i,k}$, B_i and

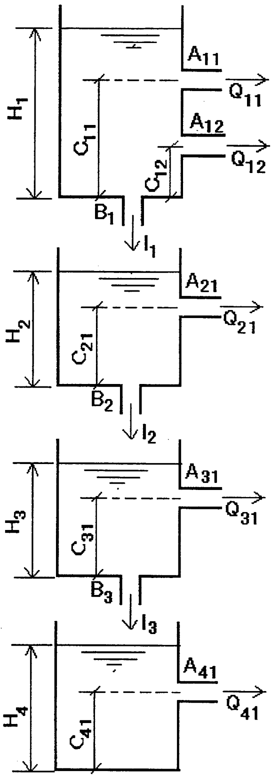


Fig. 1 Four stage tank model

$C_{i,k}$ remain constant at each time step. The changes of the water level in each tank is expressed by:

$$\frac{dH_i}{dt}=\left(Rain(t)-Evt(t)-\sum_{k=1}^{K}Q_{i,k}-I_i\right)_{i=1} \tag{3}$$

$$\frac{dH_i}{dt}=\left(I_{i-1}-\sum_{k=1}^{K}Q_{i,k}-I_i\right)_{i=2,3,4} \tag{4}$$

where *Rain(t)* is the rainfall in [mm time^{-1}] and *Evt(t)* the evapotranspiration in [mm time^{-1}]. The total runoff QT is calculated by:

$$QT=\sum_{i=1}^{N}\sum_{k=1}^{K}Q_{i,k} \tag{5}$$

2. 2 Adaptive parameter tank model by Kalman filter

When the objective of the tank model application is extended to real time forecasting of water resources, it is necessary to involve an adaptive mode in which model output may also be based on previous model input as a 'feedback' in calculating future model outputs. Such a process is generally known as a filtering technique. The most commonly applied method was developed by Kalman[10)] to estimate the state of a linear system with known system dynamics and known statistical distribution of the assumed error (i.e., noise). For the derivation of the Kalman filter algorithm, we consider a discrete, linear, state space system represented by:

State equation: $X(t+1) = \Phi(t)X(t) + u(t)$ (6)
Observation equation: $Y(t) = \Psi(t)X(t) + w(t)$ (7)

where t is the time step. X the state system vector, see **Table 1**, Φ the transition matrix, u the state system noise vector, Ψ observation transition matrix, Y the observation vector, w the observation noise vector. In the present study the extended Kalman filter (equation 8 and 9) is applied for real time rainfall-runoff prediction[11)]

$$X(t+1) = \Phi(t)X(t) + \alpha(t) + u(t) \tag{8}$$
$$Y(t) = \Psi(t)X(t) + \beta(t) + w(t) \tag{9}$$

where α is the system constant vector and β the observation constant vector.

3. The interactive user interface for the tank model

The performance and reliability of a rainfall runoff model depend primarily on four major factors[4)]: (1) the conceptual base and structure of the model, (2) the objective function (i.e., statistical criteria) to assess the simulation performance, (3) the quality and quantity of the available data for calibration and validation of the model, and (4) the performance of the calibration algorithm. The interactive user interface (IUI) for the tank model is a computer-assisted method for planning and decision making. It provides a powerful tool to alleviate the various difficulties encountered at each step of the analysis described in the interface framework given in **Fig. 2**. IUI is constructed under windows 95 on PC pentium 133, using Microsoft Visual Basic version 4.0 professional edition as a visual interface and Microsoft Fortran power station version 4.0 for numerical calculations. The main windows of the interactive user interface software are shown in **Fig.3**.

3.1 Model structure

The choice of model for a particular given condition is never a simple task. It is inevitably a subjective decision based on hydrological consideration, as well as economical constraints and personal experience and preference[2,12,13)]. Within the large number of models developed to date, conceptual rainfall-runoff models received much attention due to their simple structure and straightforward mathematical modeling of the catchment hydrologic response. In the present work 'choice of the model' was interpreted in terms of tank model structure. The tank model structure ranges from a very simple one, one tank with one side outlet (2 or 3 parameters), to a very complicated one with four tanks, each tank with four side outlets and one bottom outlet (a maximum of 40 parameters). Many different tank model configuration (i.e., number of tanks and number of holes in each tank) can be selected and evaluated during the trial and error procedure. In practice, the minimum number of parameters necessary to simulate the runoff process depends on four major factors: (1) the number and configuration of the conceptual storage units to account for the soil moisture movement in the interception, upper, lower, and ground water zones, (2) the sub-runoff process to be simulated by each side outlet, (3) the hydrologic information contained in the

Table 1 State vector for the tank model by Kalman filter

Tanks	Tank 1	Tank 2	Tank 3	Tank 4
Parameters	A_{11} C_{11} A_{12} C_{12} A_{13} C_{13} A_{14} C_{14} B_1 H_1	$A_{21}\cdots\cdots$	·····	$A_{41}\cdot\cdot B_4$ H_4
State vector	X_1 X_2 X_3 X_4 X_5 X_6 X_7 X_8 X_9 X_{10}	$X_{11}\cdots\cdots$	·····	X_{31} X_{39} X_{40}

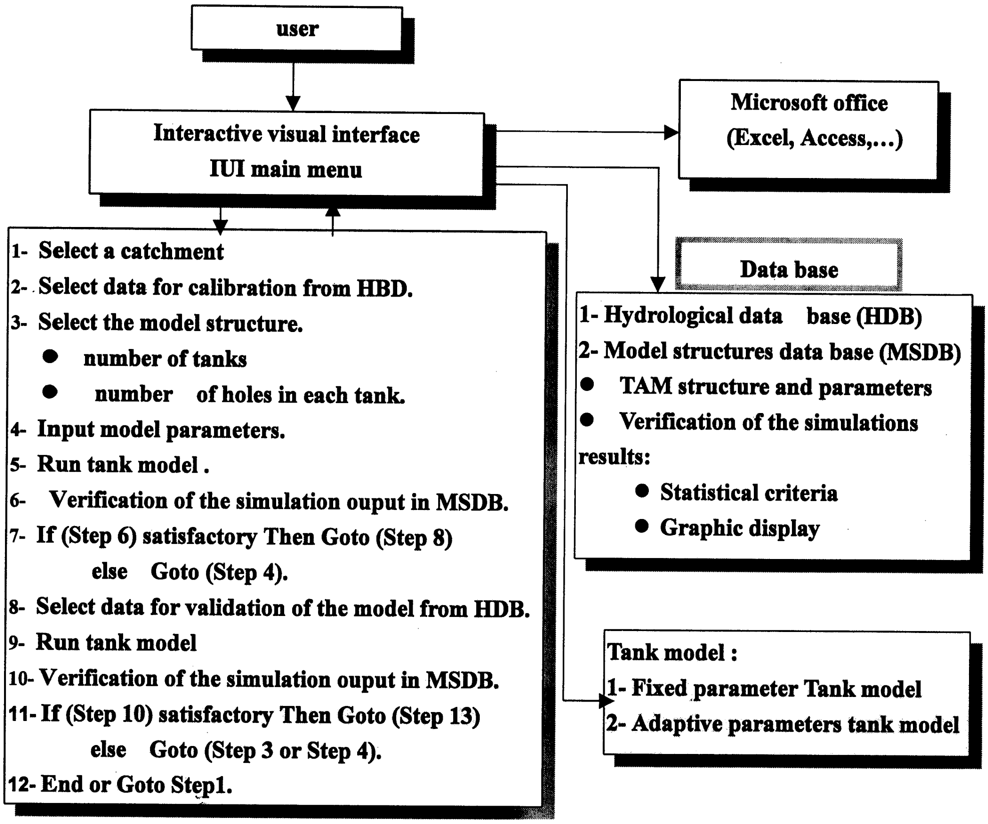


Fig. 2 Framework of the interactive user interface

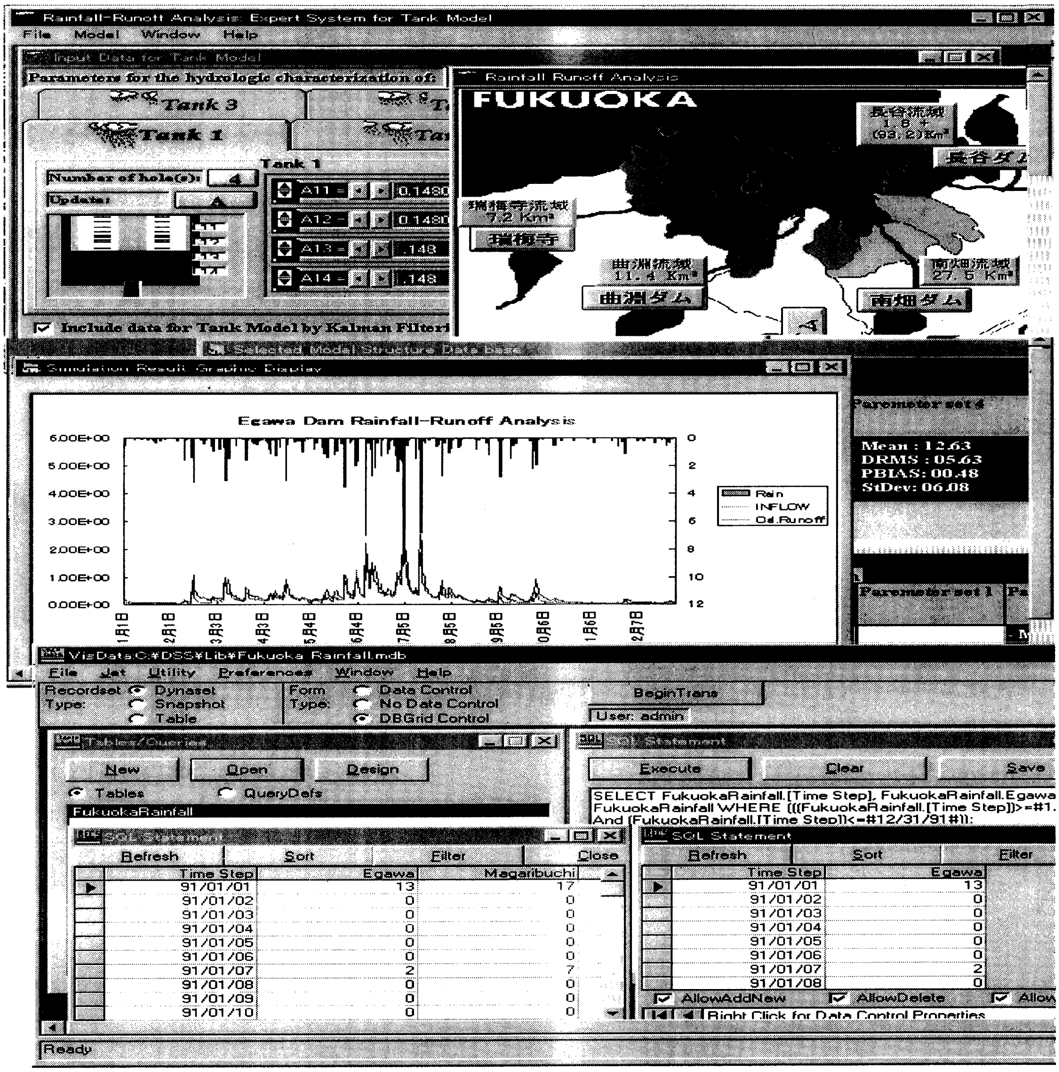
data, and (4) the objective of the model application[20]. It should be emphasized that most complex model is not necessarily the best one. Jakeman and Hornberger[14], addressed this problem and discussed the risk of over-parameterization. Beven[15], believed that "there is a great danger of over-parameterization if it is attempted to simulate all hydrological process... it appears that three to five parameters should be sufficient to reproduce most of the information in a hydrological record".

3.2 Objective function

To asses the reliability of the simulations and overcome the limitations of using a single objective function[1,2,13] the developed system estimates a number of statistical criteria for each trial. The statistical functions used are listed in the Appendix. Although the assessment of the results using several objective functions becomes more efficient than using a single criterion, a graphic evaluation of the output is necessary as a valuable indication of the hydrologic model credibility to complement the statistical functions. The graphic evaluation of the system is extended to display the total observed, simulated and predicted runoff, the runoff components (i.e., from side outlets), the infiltration or percolation process from each tank, and the variation of the parameters during the trial and error procedure or those updated by the Kalman filter method during model calibration.

3.3 Selection of data for calibration and validation of the model

In order to assess whether a calibrated model can be considered valid for subsequent use



Number of hole(s): 4

Tank 1

A11 = 0.1480
A12 = 0.1480
A13 = .148
A14 = .148

☑ Include data for Tank Model by Kalman Filteri

Mean : 12.63
DRMS : 05.63
PBIAS: 00.48
StDev: 06.08

Recordset Type: ● Dynaset ○ Snapshot ○ Table
Form Type: ○ Data Control ○ No Data Control ● DBGrid Control

User: admin

● Tables ○ QueryDefs

FukuokaRainfall

```
SELECT FukuokaRainfall.[Time Step], FukuokaRainfall.Egawa
FukuokaRainfall WHERE (((FukuokaRainfall.[Time Step])>=#1.
And (FukuokaRainfall.[Time Step])<=#12/31/91#));
```

Time Step	Egawa	Magaribuchi
91/01/01	13	17
91/01/02	0	0
91/01/03	0	0
91/01/04	0	0
91/01/05	0	0
91/01/06	0	0
91/01/07	2	7
91/01/08	0	0
91/01/09	0	0
91/01/10	0	0

Time Step	Egawa
91/01/01	13
91/01/02	0
91/01/03	0
91/01/04	0
91/01/05	0
91/01/06	0
91/01/07	2
91/01/08	0

☑ AllowAddNew ☑ AllowDelete ☑ Allow

Right Click for Data Control Properties

Ready

Fig. 3 Main windows of the interactive user interface software

it must be validated, i.e., tested against data different from those used for its calibration. The main issues involved in the validation process are: (1) how does the choice of calibration period influence the ability of the model to perform its specific task ?, and (2) how do the quality and quantity of available data affect the model performance ? These issues have been widely discussed in the literature and are not repeated here[13,16,17]. In IUI the potential user could select an appropriate period from either a graphic display or a tabulated data base using the structured query language of the integrated data base manager.

3.4 Model calibration algorithm

Global optimum parameters can be defined as uniquely optimized values that accurately represent the physical parameters of the hydrologic process approximated within the framework of the conceptual rainfall runoff model. Three approaches are used for model calibration, the trial and error method, the automatic method, and the method based on expert system. Automatic calibration methods based on optimization search algorithms have received much attention during the past two decades. Duan et al.[3] discussed the most important mathematical limitations complicating the optimization methods. Moreover two factors should be taken into consideration: first, that the choice of the objective function to be optimized represents an analysis of residuals, while completely neglecting the physical characteristics of the model, and second, the data error compensation by parameter adjustment. As a result, the parmeter values often become physically unrealistic and give poor simulation results when applied to a period different from those used for calibration. In the currently developed IUI a trial and error method is adopted and the user interface provides an easy interactive manner to update the parameters for each run. Furthermore, for each catchment, the potential user can simultaneously run, the fixed parameter tank model for several set of parameters, and the adaptive parameter tank model by Kalman filter for the same sets. For the adaptive tank model each set of parameters represent a new initial condition for the extended Kalman filter method. Each run will be incorporated into the construction of the sub-module data base for further verification and interpretation of the results. The sub-module data base obtained from several applications for real catchments will be used as a knowledge based system for future development of an expert system for the tank model.

4. The study catchments and simulation results

Five catchments representing the main water supply resources of Fukuoka city, in addition to Kuji river basin in Ibaragi prefecture were chosen for this study. The available data base represents a variety of hydrological conditions and phenomena. The data consist, except for Kuji river basin, of five years (1991 to 1995) of daily discharge from rivers in [m^3/day] and daily mean areal precipitation in [mm/day]. For Kuji river basin the data consist of one year (1994) of hourly precipitation [mm/h] and hourly runoff in [m^3/h]. The monthly evapotranspiration [mm/month] used in this study are those published in Kondo et al[18]. The periods used for model calibration and validation are shown in **Table 2**.

To calibrate the model for a given period each side outlet will reproduce a particular hydrological record. For tank 1 Q_{11} simulate the highest peak flows of the period as shown in **Fig. 4**. The amplitude of the peak is controlled by the parameter A_{11} and its apparition depend on the threshold C_{11} shown in **Fig. 5**. The peaks of smaller amplitude are simulated by Q_{12}, Q_{21} and/or Q_{31} by adjusting the parameters A_{12}, A_{21}, A_{31} and the thresholds C_{12}, C_{21} and C_{31}. If the period is characterized by more peaks amplitude variation that can be simulated by Q_{12}, Q_{21} and/or Q_{31} a third hole in the first tank characterized by A_{31} and C_{31} can be more appropriate. In general some particular events in the hydrologic records can not easily be simulated unless additional holes are adopted for a particular tank. The shape slope at recession curve governed by the parameters B_1, B_2 and B_3, and its amplitude is controlled

Table 2 Calibration and validation period selected

Catchment	Calibration period	Validation period
Egawa, Minamihata, Sefuri and Zuibaiji	From 1991/01/01 to 1991/12/31	From 1992/01/01 to 1995/12/31
Magaribuchi	From 1993/01/01 to 1993/12/31	From 1994/01/01 to 1995/12/31
Kuji river	From 04/01 to 04/20	From 07/17 to 07/26
Kuji river	From 94/06/01 to 94/06/30	From 94/08/01 to 94/08/31
Kuji river	From 08/31 to 09/02	From 09/05 to 09/16

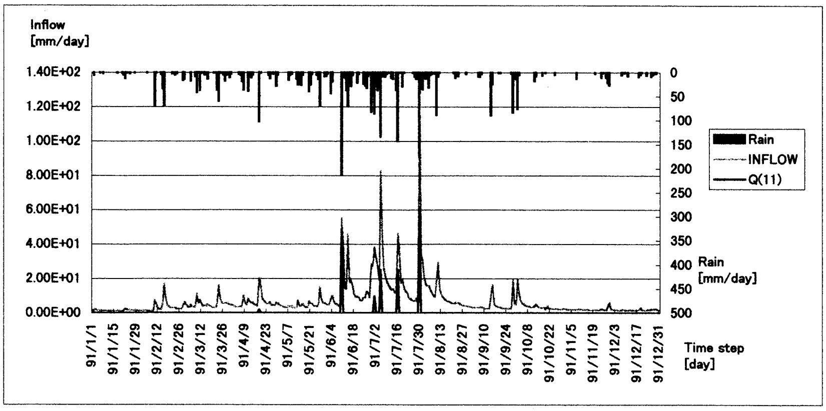


Fig. 4 Simulation of the peak runoff component by the first hole of the first tank

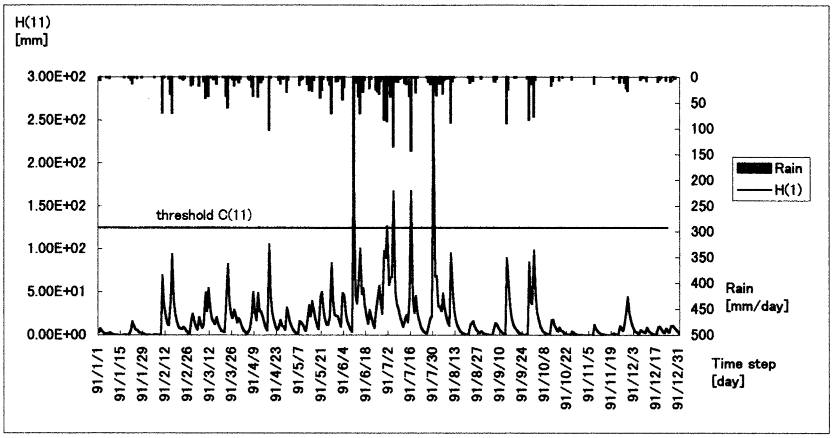


Fig. 5 Threshold of the first hole in the first tank (only the flows with H (1)> C (11) will be simulated by Q (11)

by Q_{21} and Q_{31}. Tank 4 with one side outlet Q_{41} simulate the base flow. Its value depends not only on the parameter A_{41} but is also strongly influenced by the initial value of the water level H_4. Moreover even if the base flow seems to be well simulated it happens that the water level in the tank 4 always increase. This has two possible reason, (1) the infiltration from tank 3 to tank 4 is too high or (2) that some of the infiltrated water to tank 4 does not contribute to the total runoff. In this case tank 4 should have a bottom hole to simulate the deep percolation and a threshold for the side outlet hole to better control the base flow rate.

In this study the four stage tank model presented in **Fig. 1** was applied for the characterization of the studied catchments. For each of the five catchments in Fukuoka city a unique set of parameter for calibration and validation period could be obtained. The results for Egawa and Magaribuchi catchments are shown in **Fig. 6.a, 6.b)** and **Fig. 7.a, 7.b)** respectively. The statistical criteria are shown in **Table 3**. For Kuji river basin a unique set of parameters for the whole data could not be obtained. Instead three different sets of parameter were selected to represent the runoff process variability. The main reason is the quality of the available rainfall data. Only data from one rainfall gauge situated some hundred kilometers away from the runoff measurement point in Kuji river was available. This could explain the time shifting between the rainfall event and the peak flow as can be

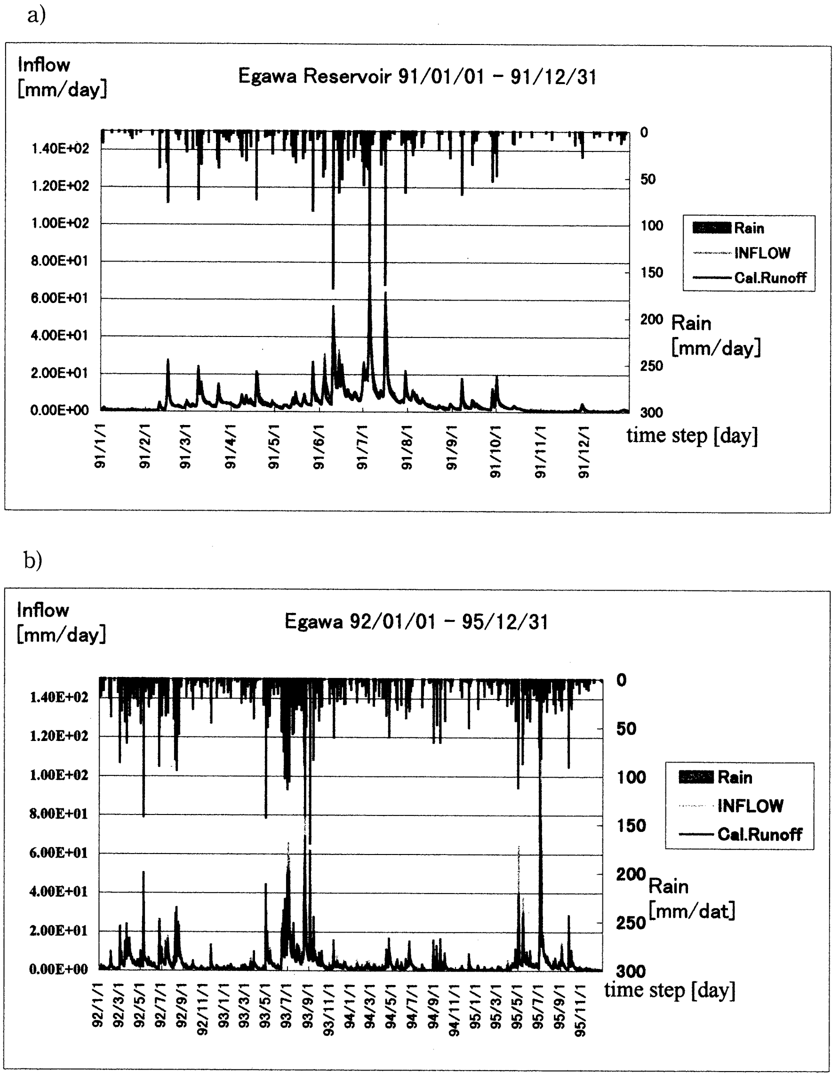


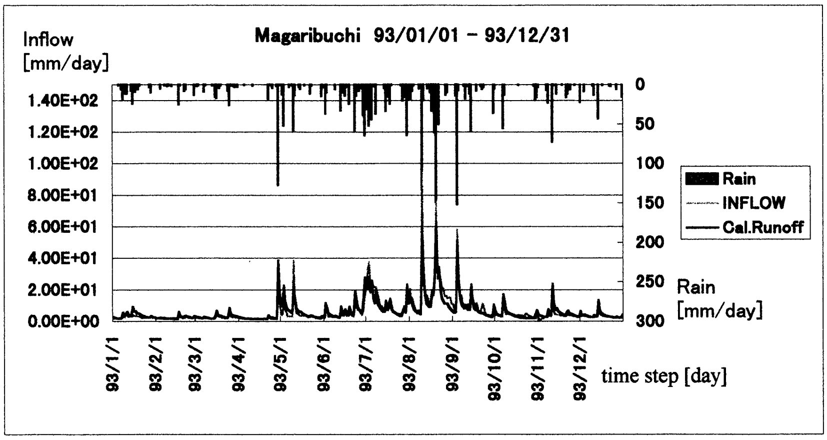
Fig. 6 a) Egawa catchment calibration period b) Egawa catchment: validation period

seen in **Fig.** 8. Moreover this time shifting has not a uniform pattern and vary from 8 hours to one day depending on the rainfall event characteristics.

Conclusion

The developed interactive user interface for the tank model has been designed to alleviate some of the major difficulties encountered in rainfall runoff analysis modeling and increase its practical utility. The interactive user interface includes the choice of model structure, the selection of the data base to be adopted for calibration and validation of the selected model and the assessment of the results using the developed data base manger. The future objective of the research presented in this paper is the development of an expert system to serve as a decision support for the tank model calibration.

a)



b)

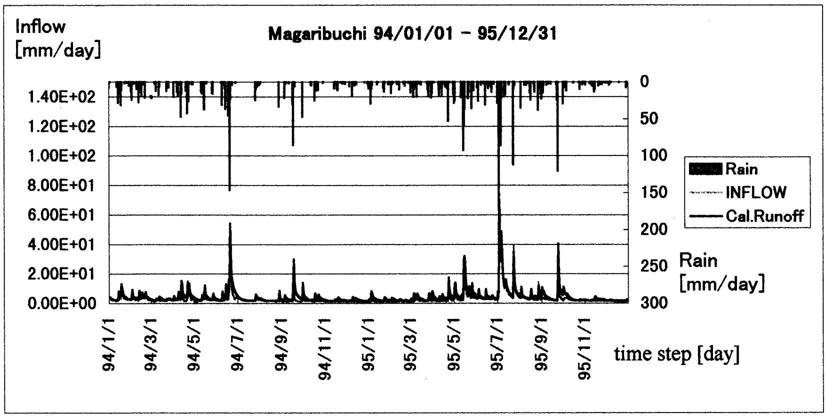


Fig. 7 a) Magribuchi catchment: calibration period b) Magribuchi catchment: Validation period

Appendix

Definition of objective function used

As mentioned above, a number of statistical criteria have been used in the developed system. According to the wide literature and research concentrated on the calibration of rainfall-runoff model[5,6,20,24,25]. The most commonly used objective functions for optimal calibration of conceptual rainfall-runoff model are defined bellow. We define by M_o and M_s the means of the observed and simulated runoff as follows:

$$M_o = \frac{1}{N}\sum_{j=1}^{N} Q_o(j)$$

$$M_s = \frac{1}{N}\sum_{j=1}^{N} Q_s(j)$$

Table 3 Statistical results (calibration period)

	Egawa (1991)	Magaribuchi (1993)	Minamihata (1991)
Mean rainfall [mm/day]	7.72	7.13	9.06
Standard deviation Rainfall [mm]	19.98	19.44	25.08
Mean observed runoff [mm/day]	5.50	6.53	7.11
Standard deviation Observed runoff [mm]	7.73	8.95	10.73
Mean simulated runoff [mm/day]	5.77	5.64	6.18
Standard deviation Simulated runoff [mm]	7.63	8.34	10.85
Bias [mm]	2.67E-01	−8.84E-01	−1.91
Relative bias	4.85E-02	−1.35E-01	−2.68E-01
Least squares error $[\mathrm{mm/day}]^2$	213.17	527.71	968.17
Mean least squares error $[\mathrm{mm}]^2$	5.84E-01	1.44E-01	2.65E-01
Log least squares error	1.64E-02	5.14E-02	8.33E-02
Forecast efficiency	−1.24E-02	−5.27E-02	−1.59E-01

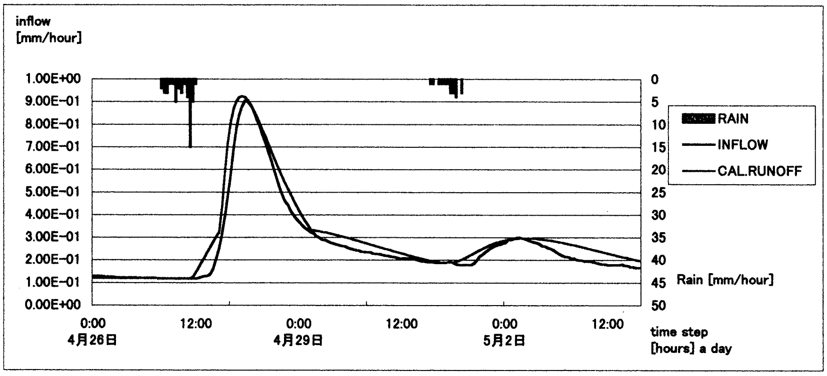


Fig. 8 Kuji river basin period form October 10th 00 : 00 h to October 26th 23 : 00 h

where $Q_o(j)$, $Q_s(j)$ are the observed and simulated runoff at time step j respectively and N is the number of hydrologic records.
The used statistical criteria are:

Bias: $$Bias = \frac{1}{N}\sum_{j=1}^{N}(Q_o(j)-Q_s(j)) \tag{A1}$$

Relative bias: $$RBias = \frac{Bias}{M_o} \tag{A2}$$

Least squares error: $$LSE = \sum_{j=1}^{N}[Q_o(j) - Q_s(j)]^2 \qquad \text{(A3)}$$

Mean Least squares error: $$MLSE = \frac{1}{N}\sum_{j=1}^{N}[Q_o(j) - Q_s(j)]^2 \qquad \text{(A4)}$$

Variance: $$VAR = (MLSE) - (Bias)^2 \qquad \text{(A5)}$$

Standard deviation: $$STD = \sqrt{\frac{1}{N}\sum_{j=1}^{N}[Q_o(j) - Q_s(j)]^2} \qquad \text{(A6)}$$

Log Least squares error: $$LSLS = \frac{1}{N}\sum_{j=1}^{N}[\log Q_o(j) - \log Q_s(j)] \qquad \text{(A7)}$$

Forecast efficiency: $$E_f = 1 - \frac{MLSE}{VAR} \qquad \text{(A8)}$$

Square of the correlation coefficient(R^2):

$$R^2 = \left[\frac{\frac{1}{N}\sum_{j=1}^{N} Q_o(j)Q_s(j) - M_oM_s}{\left(\frac{1}{N}\sum_{j=1}^{N} Q_o(j)^2 - M_o^2\right)\left(\frac{1}{N}\sum_{j=1}^{N} Q_s(j)^2 - M_s^2\right)}\right]^2 \qquad \text{(A9)}$$

The Maximum Likelihood heteroscedastic error (HMLE)[19]:

$$HMLE = \frac{\frac{1}{N}\sum_{j=1}^{N} w(j)\varepsilon(j)^2}{\left[\prod_{n=1}^{N} w(j)^2\right]^{\frac{1}{N}}} \qquad \text{(A10.1)}$$

where $\varepsilon(j) = (Q_o(j) - Q_s(j))$ is the model residual, and $w(j)$ the weight assigned to time step j, computed as:

$$w(j) = f(j)^{2(\lambda-1)} \qquad \text{(A10.2)}$$

where $f(j) = Q_{true}(j)$ is the expected true flow approximated by using either $Q_o(j)$ or $Q_s(j)$ at time step j (see Sorooshian et al., 1993), and λ the unknown transformation parameter which stabilizes the variance, calculated by the following expression using an iterative numerical procedure:

$$\left[\sum_{j=1}^{N}\ln f(j)\sum_{j=1}^{N} w(j)\varepsilon(j)^2\right] - N\left[\sum_{j=1}^{N} w(j)\ln(f(j))\varepsilon(j)^2\right] = 0 \qquad \text{(A10.3)}$$

The maximum likelihood can be evaluated more explicitly using the following rearrangement procedure:

$$R = \frac{R_d}{R_n} - 1 = 0 \qquad \text{(A10.4)}$$

where

$$R_d = \sum_{j=1}^{N} w(j)\varepsilon(j)^2 \qquad \text{(A10.5)}$$

$$R_n = \sum_{j=1}^{N} w(j)\varepsilon(j)a(j) \tag{A10.6}$$

$$a(j) = \frac{\ln f(j)}{b} \tag{A10.7}$$

$$b = \frac{1}{N}\sum_{j=1}^{N} \ln f(j) \tag{A10.8}$$

With this arrangement of terms, the *HMLE* value can be computed as:

$$HMLE = \frac{\frac{1}{N}R_d}{\exp[2(\lambda-1)b]} \tag{A10.9}$$

The procedure for estimating λ and computing *HMLE* is: (1) select $f(j) = (Q_o(j)$ or $Q_s(j))$ or $(\alpha Q_o(j)+\beta Q_s(j))$, $\alpha+\beta = 1$, α, $\beta\geq 1$, (2) compute b using (A10.8), and $a(j)$ using (A10.7), (3) use an iterative procedure to estimate λ such that $R = 0$; if the procedure requires an initial value, use $\lambda = 1$, (4) compute *HMLE* using (A10.9)[19].

References

1) Dawdy D. R. and O'Donnell T.: Mathematical models of catchment behavior, Journal of the Hydraul. Div. A SCE, 91(HY4), pp. 123-137, 1965.
2) Johnston P. R and Pilgrim D. H.: Parameter optimization for watershed models, Water Resour. Res. 12(3), pp. 477-486, 1976.
3) Duan Q., Sorooshian S. and Gupta V.: Effective and efficient global optimization for conceptual rainfall-runoff models, Water Resour. Res., 28(4), pp. 1015-1031, 1992.
4) Gan T. Y. and Biftu G. F.: Automatic calibration of conceptual rainfall-runoff models: Optimization algorithm, catchment conditions and model structure, Water Resour. Res., 32(12), pp. 3513-3524, 1996.
5) Kuczera: Efficient subspace probabilistic parameter optimization for catchment models, Water Resour. Res., 33(1), pp. 177-185, 1997.
6) Sugawara: An analysis of runoff structure about several Japanese rivers", in Japanese, Japanese Journal of Geophys., 2, 1961.
7) Sugawara M.: Runoff Analysis, in Japanese, Kyoritsu edt. p. 253, 1974.
8) Romanand Prasad: A non linear hydrologic system response model, ASCE, Journal of the Hydr. Div. Vol. 4, pp. 201-221, 1967.
9) Jermar M. K.: Water resources and water management, Development in water science, Vol. 28, pp. 33-40, 1987.
10) Athans M., Wishner R. P. and Bertolini A.: Suboptimal state estimation for continuous-time nonlinear systems from discrete noisy measurement, IEEE Transaction on automatic control, Vol. 13(5), 1968.
11) Anderson M. G. and Burt T. P.: Hydrological forecasting, Jhon Willey & Son ltd., pp. 311-435, 1985.
12) Ibbit R. P., and O'Donnell T.: Fitting methods for conceptual catchment models, Journal of the Hydraul. Div. ASCE, 97(HY9), pp. 1331-1342, 1971.
13) Diskin M. H., and Simon E. A.: Procedure for the selection of objective functions for hydrologic simulation models, Journal of Hydrology. Vol. 34, pp. 129-149, 1977.
14) Jakman A. J. and Hornberger G. M.: How much complexity is warranted in a rainfall-runoff model?, Water Resour. Res. 29(8), pp. 2637-2649, 1993.
15) Beven K.: Changing ideas in hydrology - the case of physically based model, Journal of

hydrology, Vol. 105, pp. 157-172, 1989.

16) Sorooshian S., and Dracup J. A.: Stochastic parameter estimation procedures for hydrologic rainfall-runoff models: correlated and heteroscedastic error cases, Water Resour. Res. 16(2), pp. 430-442, 1980.

17) Sorooshian S., and Gupta V. K.: Automatic calibration of conceptual rainfall-runoff models: the question of parameter observability and uniqueness, Water Resour. Res. 19(1), pp. 26-268, 1983.

18) Kondo J., Nakazono M., Watanabe T. and Kuwagata T.: Hydrological climate in Japan (3)-Evapotranspiration from forest, Journal of Japan Soc. of Hydrology & Water Resour., Vol. 5(4), pp. 8-18, (in Japanese), 1993.

19) Sorooshian S., Gupta V. K., and Fulton J. L.: Evaluation of maximum likelihood parameter estimation technique for conceptual rainfall-runoff models: Influence of calibration data variability and length on model credibility, Water Resour. Res. 19(1), pp. 251-259, 1983.