Journal of Urban and Environmental Engineering
E-ISSN: 1982-3932
celso@ct.ufpb.br
Universidade Federal da Paraíba
Brasil

Sundar Sil, Briti; Borah, Angana; Deb, Subhrajyoti; Das, Biplab

DEVELOPMENT OF RIVER FLOOD ROUTING MODEL USING NON-LINEAR MUSKINGUM EQUATION AND EXCEL TOOL 'GANetXL'

Journal of Urban and Environmental Engineering, vol. 10, núm. 2, 2016, pp. 214-220
Universidade Federal da Paraíba
Paraíba, Brasil

Journal of Urban and Environmental Engineering, v.10, n.2, p.214-220

ISSN 1982-3932
doi: 10.4090/juee.2016.v10n2.214220

Journal of Urban and Environmental Engineering

www.journal-uee.org

DEVELOPMENT OF RIVER FLOOD ROUTING MODEL USING NON-LINEAR MUSKINGUM EQUATION AND EXCEL TOOL 'GANetXL'

Briti Sundar Sil[1], Angana Borah[1], Subhrajyoti Deb[1], Biplab Das*[2]

[1]Department of Civil Engineering, NIT Silchar, India

[2]Department of Mechanical Engineering, NIT Silchar, India

Received 6 February 2016; received in revised form 8 September 2016; accepted 18 September 2016

Abstract: Flood routing is of utmost importance to water resources engineers and hydrologist. Muskingum model is one of the popular methods for river flood routing which often require a huge computational work. To solve the routing parameters, most of the established methods require knowledge about different computer programmes and sophisticated models. So, it is beneficial to have a tool which is comfortable to users having more knowledge about everyday decision making problems rather than the development of computational models as the programmes. The use of micro-soft excel and its relevant tool like solver by the practicing engineers for normal modeling tasks has become common over the last few decades. In excel environment, tools are based on graphical user interface which are very comfortable for the users for handling database, modeling, data analysis and programming. GANetXL is an add-in for Microsoft Excel, a leading commercial spreadsheet application for Windows and MAC operating systems. GANetXL is a program that uses a Genetic Algorithm to solve a wide range of single and multi-objective problems. In this study, non-linear Muskingum routing parameters are solved using GANetXL. Statistical Model performances are compared with the earlier results and found satisfactory.

Keywords: River; Muskingum; flood; spreadsheet; GaNetXL

* Correspondence to: Biplab Das. Tel.: +91 9402168938; Fax: +91 3842-224797.
E-mail: biplab.2kmech@gmail.com

INTRODUCTION

Flood routing is the method of determining the downstream outflow hydrograph using upstream inflow data in a river reach. Normally two approaches are adopted for routing of flood, firstly "hydrologic routing" and secondly "hydraulic routing". Hydrologic routing is based on the storage-continuity equation, and in hydraulic routing numerical solutions of one dimensional Saint-Venant equations or convective-diffusion equation. Singh (1988) and Akbari *et al.* (2012), showed that due to scarcity in input data and computing technology, hydrological methods are preferred. Although the Muskingum model is a sophisticated procedure to do hydrologic flood routing, it is a very popular method that describes spatially lumped form of continuity equation. McCarthy (1938) developed the Muskingum method for the study of flood routing and flood control in the Muskingum Conservancy district (Ohio) (Chin 2000). The concept of merging of prism storage and wedge storage is utilized to compute the storage volume in a channel in this method of flood routing in the particular case where inflow exceeds the outflow. Normally a negative wave is generated, in a channel when outflow is more than inflow. The basic hydrologic equation used in this Muskingum model is as follows:

$$\frac{ds}{dt} = I_{(t)} - Q_{(t)} \qquad (1)$$

where $I_{(t)}$ and $Q_{(t)}$ denote the flow rates of upstream and downstream at any instant of time (t), respectively; S is the channel storage and ds/dt is the rate of change in storage in a time interval (Δt).

The value of ds/dt depends on the storage within the reach. The change in storage value becomes positive when the storage increases and it is negative when the storage decreases (Chow, 1959). The various forms of Muskingum model may be either linear or non-linear. Depending on the channel storage, inflow/outflow discharges, hydraulic parameters, geometric parameters of the channel, the flow model is developed. Many researchers have attempted to demonstrate various methods to determine the nonlinear Muskingum models parameters (Gill, 1978; Tung, 1985; Kim *et al.*, 2001; Luo & Xie, 2010; Geem, 2006; Das, 2004; Mohan, 1997; Chu, 2009). In order to ascertain the values of the parameters in the nonlinear Muskingum model, a Least-Squares Method (LSM) was used by Gill (1978). Simultaneous nonlinear equations are solved by taking arbitrary points in LSM technique (Tung, 1985). For parameter estimation, Tung (1985) recommended the use of Hook-Jeeves (HJ) pattern search and the Conjugate Gradient (CG). He also used Davidon-Fletcher-Powell (DFP) algorithms along with the Linear Regression (LR) method. In comparison with Gill's procedure, the performance of these methods showed better results. Mohan (1997) used Genetic Algorithm (GA) for calibration of nonlinear Muskingum models and obtained results indicates that GA performs better than the other methods as it was found to have the advantage of not requiring the process of assuming initial values close to the optimal solution. Another program known as Harmony Search (HS) algorithm is implemented for calibration of the same parameter by Kim *et al.* (2001) and found better values of the parameters. Das (2004) has shown another method known as Lagrange Multiplier (LM) method to estimate the parameters for linear and nonlinear Muskingum models. In this method, unconstrained optimization problem is solved by first converting the constrained problem. Despite this improvement, Lagrange multiplier could not provide better results as compared to the earlier techniques. Geem (2006) used mathematical gradients in the Broyden-Fletcher-Goldfarb-Shanno (BFGS) technique where it requires of assumption of initial value and also it involves complicated calculus. Das (2007) formulated a complex and time consuming computational technique based on chance constrained optimization model for Muskingum model parameter estimation (Luo & Xie, 2010). Chu (2009) used Neuro-Fuzzy approach for the estimation of the Muskingum model parameters but claimed that these have no physical base. Similarly, Chu and Chang (2009) compared the parameters obtained from previous study with the parameters obtained by using Particulate Swarm Optimization (PSO) technique.

The results obtained by HS algorithms were found to give better results compared to PSO. An Immune Clonal Selection Algorithm (ICSA) was recommended by Luo and Xie (2010) to obtain the parameters of the nonlinear Muskingum model. This is a new and improved algorithm which is effective in overcoming the complexity normally arises in traditional evolutionary algorithm (Luo & Xie, 2010). Later, for this model, Barati (2011) suggests that it needs care for handling the algorithm parameters for crossover probability and mutation probability.

Furthermore, success has been achieved in hydrologic and hydraulic modeling by the use of Microsoft-Excel for the past few years. As in areas of water supply, power generation and reservoir operation excel tool has been used to solve optimization problems (Fontane, 2011). For the analysis for water distribution network, Huddleston *et al.* (2004) used Excel solver. The results revealed that the application of this procedure is a better method to solve complex engineering systems along with eliminating of computational difficulty to some extent. The use of trial and error method to solve the problems of various forms of linear and nonlinear equations in water engineering was more popular until recent times. But with the increasing popularity of excel solver, the problems associated with earlier methods can be reduced thereby producing highly accurate results in a short operating period. Wong & Zhou (2004) showed that excel solver can be used efficiently for determination of normal and critical depths for different cross sections along the flow of the channel. It can also be used for determination of critical depths just before and after a hydraulic jump. Rainfall loss constant, parameters for Horton's infiltration method, confined aquifers parameters, etc can also be computed very easily and quickly using excel tool. Lee (2003), Yidana & Ophori (2008), Lee and Noh (2003), Bhattacharjya (2011) and Grabow & McCornick (2007), and have shown other applications of Excel software.

Hence, it can be summarized that the excel solver has been skilfully used in water resources engineering problems (Huddleston *et al.*, 2004; Fontane, 2001; Wong & Zhou, 2004). In this study, also excel solver is developed to estimate the model parameters in nonlinear Muskingum model. After comparing the results obtained from the performance of this procedure with the help of performance evaluation criteria (Tung, 1985; Gill, 1978; Luo & Xie, 2010; Mohan, 1997), an observation has been put forwarded.

In the linear Muskingum model, between the inflow and outflow sections in a river reach, the storage S is given by:

$$S = K\left[XI + (1 - X)Q\right] \tag{2}$$

where K a coefficient with the dimension of travel time in the channel; and X is a dimensionless weighting factor whose values lies between 0 and 0.5. Between the inflow and outflow sections, at time increment (Δt), the storage equation can be written as follows:

$$S_t = K\left[XI_t + (1 - X)Q_t\right]; \tag{3}$$

$$S_{(t+\Delta t)} = K\left[XI_{(t+\Delta t)} + (1 - X)Q_{(t+\Delta t)}\right] \tag{4}$$

And the change in storage is given by:

$$\Delta S = S_{(t+\Delta t)} - S_t = K\begin{bmatrix}\left\{XI_{(t+\Delta t)} + (1-X)Q_{(t+\Delta t)}\right\} - \\ \left\{XI_{(t)} + (1-X)Q_{(t)}\right\}\end{bmatrix} \tag{5}$$

Equation (1) can be written in finite difference form, between the time interval (t) and $(t + \Delta t)$,

$$S_{(t+\Delta t)} - S_t = \frac{(I_t + I_{t+\Delta t})}{2}\Delta t - \frac{(Q_t + Q_{t+\Delta t})}{2}\Delta t \tag{6}$$

Combining **Eq. (5)** and **Eq. (6)**

$$Q_{(t+\Delta t)} = C_1 I + C_2 I_{(t+\Delta t)} +_t + C_3 Q_t \tag{7}$$

where,

$$C_1 = \frac{\Delta t + 2KX}{2K(1 - X) + \Delta t} \tag{8}$$

$$C_2 = \frac{\Delta t - 2KX}{2K(1 - X) + \Delta t} \tag{9}$$

$$C_3 = \frac{2K(1 - X) - \Delta t}{2K(1 - X) + \Delta t} \tag{10}$$

$$(C_1 + C_2 + C_3) = 1 \tag{11}$$

For estimation of Muskingum parameters, K and X from the available inflow and outflow data in a river reach, simple graphs can be used. The graph can be plotted, using **Eq. (3)**, between accumulated storage S and $XI + (1 - X)Q$. The graph will provide a straight line with a slope of K. Using different values for *X*; the value that gives the narrowest loop in the plotted relationship will be considered to be more correct *X* value and the slope obtained against the plotted relationship will be considered as the correct *K* value. However, it is noteworthy that there exists a loop between the curve of the weighted-discharge and storage as the rising limb of the flood wave is at higher level than the falling limb and vice versa corresponding to the storage of the steady flow condition (Chow, 1959). In this procedure, it requires a lot of time as it involves hit and trial method and as a result there is a development of various other numerical methods.

It has been generally observed that in natural channel reaches, the use of the linear Muskingum model could lead to erroneous results in the forecast of flood behavior because it is characterized by nonlinear storage-discharge relationship (Gill, 1978; Tung, 1985). The problem of linearity has been resolved by the use of the following three forms of nonlinear Muskingum (Papamichail & Georgiou, 1994; Gill, 1978; Chow, 1959; Luo & Xie, 2010; Mohan, 1997) and they are:

$$S = K[XI^p + (1 - X)Q^p] \tag{12}$$

$$S = K[XI^{p_1} + (1 - X)Q^{p_2}] \tag{13}$$

$$S = K[XI + (1 - X)Q]^m \tag{14}$$

Considering the effects of nonlinearity between the storage volume and weighted-flow, in **Eq. (12)**, **Eq. (13)** and **Eq. (14)**, additional fitting parameters p, p1 and m are used respectively. For comparison of the study, **Eq. (12)** which is another form of non-linear Muskingum equation is considered for simulation and forecasting of the model. In recent years, the use of spreadsheets among the researchers and engineers gaining popularity because of their ease of use, strong graphical interface and ability to solve iterative solution and also customization of various software which can used as add-in in Microsoft excels (Karahan *et al.*, 2005; Karahan, 2008). In this study, "GaNetXL" application running under Microsoft Excel is used in the optimization processes.

Simulation model

Rearranging **Eq. (12)** in the form of **Eq. (7)**, the rate of outflow at a time t is given by

$$Q_t = \left(\frac{1}{1-X}\right)\left(\frac{S_t}{K}\right)^{1/m} - \left(\frac{X}{1-X}\right)I_t \qquad (15)$$

From **Eq. (1)**, the change in storage for a time interval of time between (t) and $(t+\Delta t)$, with increment of time (Δt) is given as:

$$\frac{\Delta S}{\Delta t} = -\left(\frac{1}{1-X}\right)\left(\frac{S_t}{K}\right)^{1/m} + \left(\frac{1}{1-X}\right)I_t \qquad (16)$$

The next accumulated storage can be expressed as:

$$S_{t+1} = S_t + \Delta S \qquad (17)$$

The routing procedure is described as follows (Barati, 2012; Tung, 1985; Kim *et al.*, 2001)

Step 1: Using optimization routine, hydrologic parameters (K, X, and m) given in **Eq. (14)** are determined.

Step 2: Initial storage volume is computed by **Eq. (14)**, where the initial inflow and outflow are same.

Step 3: Using **Eq. (16)**, change in storage for a time interval (Δt) is calculated.

Step 4: From **Eq. (14)** and **Eq. (16)**, estimate the next accumulated storage by using **Eq. (17)**.

Step 5: Finally, compute the outflow for the next time by using **Eq. (15)**.
Using the above procedure ordinates of all the outflow discharge can be calculated.

GANetXL

The optimization GANetXL was developed at the Centre for Water Systems (CWS) of the University of Exeter for over a decade (Morley *et al.*, 2001). GANetXL is an add-in for Microsoft Excel, spreadsheet application for Windows and MAC operating systems. Excel supports programming with Visual Basic for Applications (VBA). GANetXL is a program that uses a Genetic Algorithm to solve a wide range of single and multi-objective problems. For single-objective problems GANetXL provides a family of steady-state, generational and generational elitist evolutionary algorithms (Goldberg, 1989) whereas in the domain of multi-objective problems the (non-dominated sorting genetic algorithm-II) NSGA-II algorithm (Deb *et al.*, 2002) is supported. The benefit of this add-in program is its ease of use and the implementation of a Genetic algorithm (GA) in a spreadsheet environment that can be applied to a variety of problems. The detail process of GANetXL is explained in the manual of GANetXL 2006, (http://centres.exeter.ac.uk/cws/downloads/cat_view/25-software/42-ganetxl)

Statistical performance evaluation

To measure the efficacy of the GANetXL and the estimated parameters the evaluation criteria adopted are briefly described as follows. The performance of the developed model are tested using some standard statistical measures such as coefficient of correlation (*CORR*), sum of squared error (*SSE*) and Nash-Sutcliffe -coefficient of efficiency (*CE*).These statistical criterion represents the performance of the developed model and represent the stability of the estimated values with that of the real values. The coefficient of correlation (*CORR*) describes the matching flow between the modeled data and observed data set. Nash-Sutcliffe model "efficiency coefficient" (*CE*) is an important statistic describing model fitness and closeness between the observed and predicted values. A value of *CE* = 1indicates perfect model fit while, *CE* = 0 represents that the model is as good as the mean model.

Sum of squared error (SSE)

Sum of squared error is the summation of the differences between observed and the modeled value. The lesser the *SSE*, the better the model fitness.

$$SSE = \sum_{t=1}^{N} \left((O)_o^t - (O)_m^t\right)^2 \qquad (18)$$

where:

$(O)_o^t$ = observed value at time 't'.

$(O)_m^t$ = modeled value at time 't'.

N = total number of pairs of hydrograph ordinates data.

$$\text{Corr}=\frac{N\sum_{i=1}^{T}\left(O_o^t\left(O_m^t\right)\right)-\sum_{i=1}^{T}\left(O_o^t\sum_{i=1}^{T}\left(O_m^t\right)\right)}{\sqrt{\left(N\sum_{i=1}^{T}\left(\left(O_o^t\right)\right)^2-\left(\sum_{i=1}^{T}\left(\left(O_o^t\right)\right)^2\right)\right)\left(N\sum_{i=1}^{T}\left(\left(O_m^t\right)\right)^2-\left(\sum_{i=1}^{T}\left(\left(O_m^t\right)\right)^2\right)\right)}} \quad (19)$$

Coefficient of correlation (CORR)

The coefficient of correlation represents the measurement of strength of a linear relationship between the observed and estimated variables. Its value can be calculated using **Eq. (19)** as given below. Normally the calculated value ranges between +1 to -1. A brief description of the values are given below to interpret the relationship between the observed and estimated values.

- If the value is '-1', it indicates negative linear relationship which means that one of the variable changes (either increases or decreases) if the other one changes (decreases or increases) considering the linear rule.
- If the value is '0', it indicates that there is no linear relationships between the two sets.
- And if the value is '+1', it indicates a good positive linear relationship between the variables. It means that if one variable increases, the other variable also will increase following the same linear rule.

Nash Sutcliffe co-efficient of efficiency (*CE*)

This is one of the popular statistical evaluation criteria normally used in hydrological models to understand the goodness of data sets. The formula used for this criteria is given in **Eq. (10)**. The value of *CE* ranges from '0' to '1' but sometimes its value becomes negative, and which is also normally considered. If the calculated *CE* is '1', it represents a perfect model and if the value of *CE* is '0' or near to '0', then it means that the model is not working well.

$$CE = 1-\frac{\sum_{t=1}^{T}\left(\left(O\right)_o^t-\left(O\right)_m^t\right)^2}{\sum_{t=1}^{T}\left(\left(O\right)_o^t-\overline{\left(O\right)}_o\right)^2} \quad (20)$$

$\overline{\left(O\right)}_o$ = mean of observed outflow.

Methodology and Model Application

In spreadsheet, using GANetXL as an add-in, the non-linear Muskingum equation is modeled in discrete time step variable. The equation used for modeling is given in **Eq. (21)**.

$$SSE=\sum_{t=1}^{N}\left\{\left(O\right)_o^t-\left(\frac{1}{1-X}\right)\left(\frac{S_t}{K}\right)^{1/m}-\left(\frac{X}{1-X}\right)I_t\right\}^2 \quad (21)$$

Subject to:

$$0\le X\le 0.5 \quad (22)$$

Equation (21) is important to be considered for simulation as the storage is a function of both inflow and outflow. Here X is a weighing factor, when X = 0, it means that storage is a function of outflow only and when X= 0.5, both the inflow and outflow are equally important in determining the storage. The significance of X for different condition is described in the book of Chow, 1959. The other two parameters are viz. K, which is storage time constant (normally positive value), and m, is a constant exponent. Here, SSE is the main objective function.

Following the common tradition in research, the present study uses the inflow and outflow discharge of a single flood event given by Wilson (1974) which has also been extensively used by others (Al-Humoud & Esen, 2006; Gill, 1978; Tung, 1985; Yoon & Padmanabhan, 1993; Mohan, 1997; Kim *et al.*, 2001;; Geem, 2006; Chu, 2009; Luo & Xie, 2010; Chu & Chang, 2009).

For parameter estimation of the nonlinear Muskingum model using spreadsheet is shown in **Fig. 1**. Using GANetXL, where the embedded GA based optimization technique is used, the simulation of the model is carried out. In the spreadsheet, during the simulation, routing procedures can be observed. A simple skill is required to make the procedure to be more comfortable and useful to the users. In the spreadsheet, the values of time, inflow and outflow can be visualized as given in the **Fig. 1**. Also the lower and upper limits for the parameters x, k and m are fixed so as to ease the search space. In the spreadsheets the cell F5, G5 and H5 representing x, k and m respectively are adjustable cells. The GANetXL solver.

In this way the final values are determined through iterations and hence its shows that GANetXL can be used efficiently for parameter estimation. The values of ΔS/Δt, ΔS, S, and Q are stored in K3 to K24, L3 to L24, M3 to M24, and N3 to N24 cells respectively. The performance evaluation criteria is shown by a comparison of the statistical findings *CE*, *CORR and SSE* for different methods and GANetXL which is shown in **Table 1**.

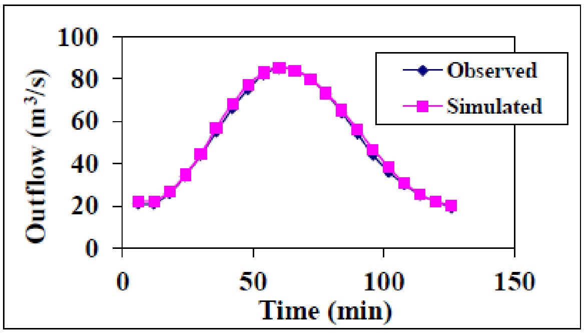
Time	I	Q_{obs}
0	22	22
6	23	21
12	35	21
18	71	26
24	103	34
30	111	44
36	109	55
42	100	66
48	86	75
54	71	82
60	59	85
66	47	84
72	39	80
78	32	73
84	28	64
90	24	54
96	22	44
102	21	36
108	20	30
114	19	25
120	19	22
126	18	19

	x	k	m
Limit(lower)	0.5	10	10
Limit (upper)	0	0.01	0.01
Optimal	0.27769	0.08620	1.8683

C1	0.9318369
C2	0.8466909
C3	-0.778528
Constraint 1	1
Constraint 2	0
Δt	1

Performance statistics for Discharge

CE	0.9967
Correlation	0.9994
SSE	3.810E+01



ΔS/Δt	ΔS	S	Q_{cal}	$(Q_{obs} - Q_{cal})^2$
-	-	27.77	22	0.00000
1.384	1.384	29.15	22.000	1.00000
17.195	17.195	46.35	22.419	2.01322
58.23	58.23	104.58	26.610	0.37255
80.663	80.663	185.24	34.639	0.40881
69.566	69.566	254.81	44.510	0.25997
51.145	51.145	305.95	57.086	4.35172
28.423	28.423	334.37	68.117	4.47963
3.683	3.683	338.06	76.934	3.74175
-17.762	-17.762	320.30	82.995	0.99045
-31.071	-31.071	289.22	85.457	0.20909
-41.691	-41.691	247.53	84.078	0.00603
-44.232	-44.232	203.30	80.157	0.02459
-44.1	-44.1	159.20	73.409	0.16754
-38.793	-38.793	120.41	65.256	1.57665
-33.563	-33.563	86.85	56.025	4.09945
-25.615	-25.615	61.23	46.846	8.09838
-17.433	-17.433	43.80	38.048	4.19568
-11.182	-11.182	32.62	30.797	0.63573
-6.892	-6.892	25.72	25.508	0.25803
-2.931	-2.931	22.79	21.931	0.00470
-2.483	-2.483	20.31	20.098	1.20650
				38.10046

Fig. 1 Representation of the model in spreadsheet format.

Table 1. Results of the performance evaluation criteria

	LSM	HJ+DFP	ICSA	GRG	GA(present study)
CE	0.9881	0.9962	0.9968	0.9970	0.9967
CORR	0.9949	0.9991	0.9996	0.9995	0.9994
SSE	145.71	46.66	38.84	36.77	38.10

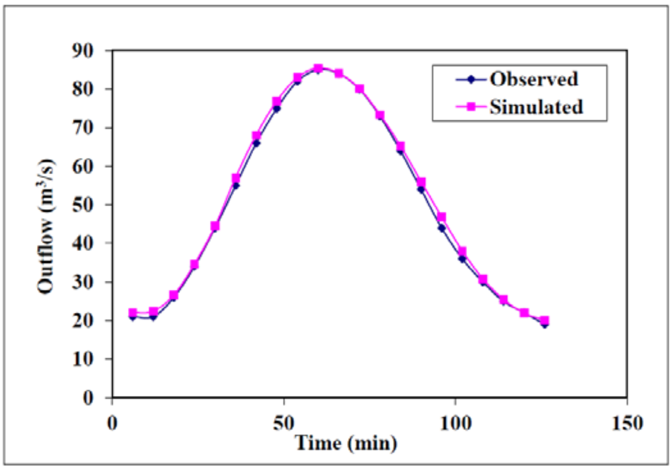


Fig. 2 Outflow hydrograph of observed and simulated discharge.

RESULTS AND DISCUSSION

The objective of this model is to show accuracy in measurements by methods using GANETXL and a close comparison with the actual observed data. And hence, emphasize GANetXL as an efficient tool at relatively easier procedure. It is simple to infer from the graphical representation in **Fig. 2** that the outflow hydrograph of the simulated model closely follows the hydrograph obtained from the observed data. This has been validated by showing a comparison of the performance evaluation criteria given by **Eqs (17)**, **(18)** and **(19)** by means of various methods consisting of LSM, HJ+DFP, ICSA (Luo & Xie, 2010), GRG solver which are tabulated in **Table 1**. From the results it can be indicated that the use of Excel solver is proficient in evaluating the parameters of nonlinear Muskingum routing models.

CONCLUSIONS

The use of GANetXL which is an optimisation add-in for Microsoft excel has been portrayed in this paper. The result is shown to be comparable to the output of the various other studies done by different methods. Hence, this is an attempt to show that for relatively simpler model GANeTXL is an efficient tool to analyse a problem and that it absolves the researcher of solving complex and tedious mathematical equations manually which is time consuming and vulnerable to errors. The information required for configuration and execution of the method has been taken from GANeTXL-user manual, University of Exeter. Although there are certain limitations in using the tool as mentioned in results and discussion, it has scope for future improvement.

REFERENCES

Akbari, G.H., Nezhad, A.H., Barati, R. (2012) Developing a model for analysis of uncertainties in prediction of floods. *J. Adv. Res.* **3**(1), 73–79. Doi: 10.1016/j.jare.2011.04.004

Al-Humoud, J. M. and Esen, I. I. (2006). Approximate methods for the estimation of Muskingum flood routing parameters. *Water Resour. Manag.* **20**(6), 979–990. Doi:10.1007/s11269-006-9018-2

Barati, R. (2012) Application of Excel Solver for Parameter Estimation of the Nonlinear Muskingum Models. *KSCE J. Civil Enging.* **17**(5):1139-1148. Doi: 10.1007/s12205-013-0037-2.

Bhattacharjya, R.K. (2011) Solving groundwater flow inverse problem using spreadsheet solver. *J. Hydrol. Engng.* **16**(5), 472–477. Doi 10.1061/(ASCE)HE.1943-5584.0000329

Chin, D. (2000) *Water Resources Engineering*. New Jersey: Prentice Hall.

Chow, V.T. (1959) *Open channel hydraulics*. McGraw-Hill, New York, p. 680.

Chu, H. J. (2009) The Muskingum flood routing model using a neurofuzzy approach. *KSCE J. Civil Engng.* **13**(5), 371–376. Doi: 10.1007/s12205-009-0371-6

Chu, H.J. & Chang, L.C. (2009) Applying particle swarm optimization to parameter estimation of the nonlinear Muskingum model. *J. Hydrol. Engng.* **14**(9), 1024–1027. Doi: 10.1061/(ASCE)HE.1943-5584.0000070

Das, A. (2004). Parameter estimation for Muskingum models. *J. Irrig. Drain. Enging.* **130**(2), 140–147. Doi: 10.1061/(ASCE)0733-9437(2004)130:2(140)

Das, A. (2007) Chance-constrained optimization-based parameter estimation for Muskingum models. *J. Irrig. Drain. Engng.* **133**(5), 487–494. Doi: 10.1061/(ASCE)0733-9437(2007)133:5(487)

Fontane, D. (2001) Multi-objective simulation and optimization of reservoir operation using Excel. *Proc. Second Federal Interagency Hydrologic Modeling Conference*. Las Vegas, NV, USA.

Gill, M.A. (1978) Flood routing by Muskingum method. *J. Hydrol.* **36**(3-4), 353–363. Doi: 10.1016/0022-1694(78)90153-1

Goldberg, D. E. (1989) *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison- Wesley, Reading, MA.

Grabow, G.L. & McCornick, P.G. (2007) Planning for water allocation and water quality using a spreadsheet-based model. *J. Water Resour. Plann. Managem.* **133**(6), 560–564. Doi: 10.1061/(ASCE)0733-9496(2007)133:6(560)

Huddleston, D.H., Alarcon, V.J., Chen, W. (2004) Water distribution network analysis using Excel. *J. Hydr. Engn.* **130**(10), 1033–1035. Doi: 10.1061/(ASCE)0733-9429(2004)130:10(1033)

Karahan, H. & Ayvaz, M.T. (2005) Transient groundwater modeling using spreadsheets. *Adv. Engng. Softw.* **36**, 374–384. Doi: 10.1016/j.advengsoft.2005.01.002

Karahan, H. (2008) Solutions of weighted finite difference techniques with the advection-diffusion equation using spreadsheets. *Comput. Appl. Eng. Educ.* **16**(2), 147–156. Doi: 10.1002/cae.20140

Kim, J.H., Geem, Z.W., Kim, E.S. (2001) Parameter estimation of the nonlinear Muskingum model using harmony search. *J. Amer. Water Resour. Assoc.* **37**(5), 1131–1138. Doi: 10.1061/(ASCE)HE.1943-5584.0000608

Lee, J.S. & Noh, J.W. (2003) The impacts of uncertainty in the predicted dam breach floods on economic damage estimation. *KSCE J. Civil Engng.* 7(3), 343–350. Doi: 10.1007/BF02831783

Lee, J.S. (2003) Uncertainties in the predicted number of life loss due to the dam breach floods. *KSCE J. Civil Engng.* **7**(1), 81–91. Doi: 10.1007/BF02841991

Luo, J. & Xie, J. (2010) Parameter estimation for nonlinear Muskingum model based on immune clonal selection algorithm. *J. Hydr. Engn.* **15**(10), 844–851. Doi: 10.1061/(ASCE)HE.1943-5584.0000244

McCarthy, G. T. (1938) The unit hydrograph and flood routing. *Proc. Conference of North Atlantic Division*, U.S. Army Corps of Engineers, Rhode, Island.

Mohan, S. (1997) Parameter estimation of nonlinear Muskingum models using genetic algorithm. *J. Hydr. Engn.* **123**(2), 137–142. Doi: 10.1061/(ASCE)0733-9429(1997)123:2(137)

Papamichail, D. & Georgiou, P. (1994) Parameter estimation of linear and nonlinear Muskingum models for river flood routing. *Trans. Ecol. Environ.* **7**, 1743–3541.

Savić, D.A., Bicik, J., Morley, M.S. (2011) A DSS generator for multi objective optimisation of spreadsheet-based models. *Environm. Modelling Softw.* **26**(5), 551–561. Doi: 10.1016/j.envsoft.2010.11.004

Singh V.P. (1988) *Hydrologic systems: Rainfall-runoff modelling*. . Vol. 1, Prentice Hall, NJ, 1988.

Tung, Y.K. (1985) River flood routing by nonlinear Muskingum method. *J. Hydr. Engn.* **111**(12), 1447–1460. Doi: 10.1061/(ASCE)0733-9429(1985)111:12(1447)

Wilson, E.M. (1974) *Engineering hydrology*. MacMillan, Hampshire, UK.

Wong, T.S.W. and Zhou, M.C. (2004) Determination of critical and normal depths using excel. *Proc. World Water and Environmental Resources Congress*, Salt Lake City Utah, USA.

Yidana, S.M. & Ophori, D. (2008) Groundwater resources management in the Afram plains area, Ghana. *KSEC J. Civil Engng.* **12**(5), 349–357. Doi:10.1007/s12205-008-0349-9

Yoon, J.W. & Padmanabhan, G. (1993) Parameter estimation of linear and nonlinear Muskingum models. *J. Water Resour. Plann. Managem.***119**(5), 600–610. Doi: 10.1061/(ASCE)0733-9496(1993)119:5(600)