

FLOW ROUTING CALCULATIONS FOR WATER RESOURCES MANAGEMENT USING SPREADSHEETS

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ABSTRACT

Flow routing calculations are very important for water resources engineers for analyzing and designing water engineering systems such as reservoirs, stormwater conduits and detention ponds, spillways, pumping stations, etc. The present paper introduces spreadsheets as an efficient computational tool to carry out routing calculations. After reviewing many of the flow routing procedures used by engineers and their applications for reservoir, river and catchment routing, a series of examples are worked out to illustrate the use of spreadsheets to carry out the routing calculations for the selected procedures. The paper emphasizes the superiority of spreadsheets over other available methods as a computational tool for routing calculations. Spreadsheets are both valuable for design purposes, and an excellent educational tool in the area of computational hydrology.

Key words: Flow Routing (Reservoir, River, Watershed), Computational Hydrology, Water Resources Management.

INTRODUCTION

Flow routing is a procedure for determining the time and magnitude of flow (i.e., the flow hydrograph) at a point on a watercourse from known or assumed hydrograph at one or more points upstream. In a broad sense, flow routing may be considered as an analysis to trace the flow through a hydrologic system for a given input.

Flow routing procedures route hydrographs over land, through conduits or through reservoirs, to analyze the effects of conduit modifications,

Aly N. El-Bahrawy

in land use, and overtopping of highway embankments. Flood warning systems use flood routing to predict flow stages before the actual stages are realized. Also, the routing models are useful for applications in stormwater detention pond design. The use of routing procedures is not limited to humid regions, it is also used, in arid regions where no rivers exist, to design storm water collection systems.

Flood routing calculations can be made by hand, using a calculator, graphically, using design charts or using computers. The use of computers to carry out calculations can be accomplished either by writing a high-level language program, such as FORTRAN, PASCAL, C++, etc, or using commercially available software designed to solve a specific routing problem. In both cases the engineer is faced with some difficulty: he has to learn programming in the first case, and he has to accept the results of the 'black box' model in the second case. Writing a routing program, however, gives the engineers full control over the method used, the type of calculations, and how the output results are displayed. Using commercial software, on the other hand, will deprive the engineer from such flexibilities. Other computer programs, such as spreadsheets, allow the engineer to write his own program without the need to learn high level programming, or be forced to accept the assumptions and formats of the commercial package. Some of the commercial software concerned with routing are: WASSP, HEC-1, HYMO, MIDUSS, etc. A guide for such software used for water management is given in (1).

The calculations encountered in flow routing can be arranged in table or matrix form where each cell represents the flow value at a certain time or location. Plotting the resulting outflow hydrograph and comparing it with the inflow gives insight about the ability of the numerical routing procedure used to simulate the actual outflow obtained from an analytical solution or from actual measurements in the field. Spreadsheets are a computational means that can be used efficiently for many engineering and water resources calculations (2,3,4,5,6), and can provide an excellent design and educational tool when used for flow routing. Visibility of spreadsheet calculations, and the capability of performing 'what if' and sensitivity analyses help engineering students better understand the details of calculations, as well as the concepts behind each routing procedure. The nature of flow routing calculations, where each cell represents a value of flow calculated using data from the previous time step and/or location, allows the engineer to use the worksheet, which is composed of intersecting rows and columns, to readily calculate the different values in

Flow Routing Calculations for Water Resources Management.....

the cells. Also, the ability to produce instant graphs from the calculated data, gives the engineer the advantage of visually inspecting the results, as well as being able to compare different routing procedures for design purposes.

CLASSIFICATION OF FLOW ROUTING

Routing can be generally classified as lumped system (hydrologic routing), or distributed system (hydraulic routing). The difference is that in a lumped system, the flow is calculated as a function of time alone at a particular location, while in a distributed system the flow is calculated as a function of space and time throughout the system. Hydrologic models use the continuity equation and mathematical relationships between discharge and storage, and usually have a closed-form solution equation. Hydraulic models use both the continuity and momentum equations, and usually require some form of numerical integration.

Lumped Flow Routing

For a hydrologic system, input (I), output (Q), and storage (S) are related by the continuity equation:

$$\frac{dS}{dt} = I(t) - Q(t) \quad (1)$$

If the inflow hydrograph $I(t)$ is known, the above equation cannot be solved directly to obtain the outflow hydrograph $Q(t)$, since both Q and S are unknown. A second relationship, i.e. storage function, is needed to relate S , I , and Q . The two relationships provide a solvable combination of two equations and two unknowns. The specific form of the storage function to be employed in this procedure depends on the nature of the system being analyzed.

Reservoir Routing

A reservoir is a natural or artificial feature designed to store incoming water and release it at regulated rates, for diverse uses, including hydropower generation, municipal and industrial water supply, flood control,

Aly N. El-Bahrawy

irrigation, navigation, fish and wildlife management, water quality, and recreation.

An example of reservoir routing is the level pool routing, in which the storage function has the form:

$$S = f(Q) \quad (2)$$

where $f(Q)$ is determined by relating reservoir storage and outflow to reservoir water level. The storage function represented by eqn (2) is single-valued or invariable and applies to a reservoir with a horizontal water surface, which has a wide and deep pool compared to its length in the direction of flow. This invariable storage relationship requires that there be a fixed discharge from the reservoir for a given water surface elevation (H).

The level pool routing procedure divides the time horizon into intervals, and assumes that the variation of inflow and outflow is approximately linear. Eqn (1) can be written as:

$$S_{j+1} - S_j = \frac{I_j + I_{j+1}}{2} \Delta t - \frac{Q_j + Q_{j+1}}{2} \Delta t \quad (3)$$

Eqn (3) is solved by isolating the unknowns Q_{j+1} and S_{j+1} , and using a storage-outflow function relating $(2S/\Delta t) + Q$ and Q , which can be developed using elevation-storage and elevation-outflow relationships (7).

An alternative method for level pool routing can be developed by solving the continuity equation using a numerical method such as the Runge-Kutta method (8). Various orders of Runge-Kutta schemes can be adopted. As an example, the third order scheme involves breaking each time interval into three increments and calculating successive values of water surface elevation (H) and reservoir discharge for each increment (7). The continuity equation is expressed as:

$$\frac{dS}{dt} = I(t) - Q(H) \quad (4)$$

Flow Routing Calculations for Water Resources Management.....

Expressing the change in storage as $dS=A(H)dH$, where $A(H)$ is the water surface area at elevation H , the continuity equation is then rewritten as:

$$\frac{dH}{dt} = \frac{I(t) - Q(H)}{A(H)} \quad (5)$$

The solution is extended forward by three increments in each time interval Δt , and three successive approximations are made for the change in head elevation dH .

River Routing

The Muskingum method is a commonly used hydrologic routing method for handling a variable discharge-storage relationship. This method models the storage volume of flooding in a river channel by a combination of a wedge storage resulting from the advance and recession of flood wave, and a prism storage resulting from volume of constant cross section along the length of prismatic channel. If the cross section of the flood flow is directly propoto the discharge at the section, the prism storage is equal to KQ , and the wedge storage is equal to $KX(I - Q)$, where $0 \leq X \leq 0.5$. The total storage is therefore,

$$S = KQ + KX(I - Q) \quad (6)$$

from which the storage function can be expressed as:

$$S = K[XI + (1 - X)Q] \quad (7)$$

The parameter K is the time of travel of the flood wave through the channel reach. Expressing the values of storage at time j and $j+1$ and using eqn (7), combining the result with equation (3) and simplifying, the following routing equation is obtained:

$$Q_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 Q_j \quad (8)$$

where C_1 , C_2 , and C_3 are functions of K, X , and Δt . The values of K and X can be determined from observed inflow and outflow hydrographs for a river reach.

Watershed Routing

A watershed may be represented by a series of n identical linear reservoirs. A linear reservoir is one whose storage is linearly related to its output by a storage constant k , which has the dimension of time,

$$S = kQ \quad (9)$$

By routing a unit volume inflow through the n linear reservoirs, a mathematical model for the instantaneous unit hydrograph (IUH) of the series can be derived. The outflow q_n from the n th reservoir is calculated as:

$$u(t) = q_n(t) = \frac{1}{k\Gamma(n)} \left(\frac{t}{k}\right)^{n-1} e^{-t/k} \quad (10)$$

where $u(t)$ is the unit hydrograph, and $\Gamma(n)=(n-1)!$. Mathematically the equation is a gamma probability distribution function. The values of n and k in eqn (10) can be calculated by the method of moments given the excess rainfall hydrograph and the direct runoff hydrograph (7).

Another solution to the linear reservoir problem can be obtained by substituting eqn (9) in eqn (3) and solving for Q_{j+1} to get a relationship similar to eqn (8), where the three constants are functions of Δt and k (9). The cascade of n linear reservoirs can be modeled by taking the flow from the first reservoir as the inflow to the second and so on.

Distributed Flow Routing

The flow of water through the soil and stream channels of a watershed is a distributed process because the flow rate, velocity, and depth vary in space throughout the watershed. Estimates of the flow rate or water level at important locations in the channel system can be obtained using a distributed flow routing model. This type of model is based on partial differential equations, i.e. the Saint-Venant equations for one-dimensional flow, that allow the flow rate and water level to be computed as functions of space and time, rather than of time alone in the lumped models described above.

Flow Routing Calculations for Water Resources Management.....

The Saint-Venant equations: the continuity and momentum, have various simplified forms, each defining a one dimensional distributed routing model. The equations can be written in either the conservation form where the dependent variable is the average flow velocity V , or the nonconservation form, where the dependent variable is the channel flow Q . The conservation form of the equations neglecting lateral inflow, wind shear, and eddy losses, are written as:

continuity equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \quad (11)$$

momentum equation

$$\frac{1}{A} \frac{\partial Q}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} \left(\frac{Q^2}{A} \right) + g \frac{\partial y}{\partial x} - g(S_o - S_f) = 0 \quad (12)$$

The momentum equation consists of terms for the physical processes that govern the flow momentum. These terms shown in eqn (12) are respectively: the local acceleration, the convective acceleration, the pressure force, the gravity force, and the friction force. Alternative distributed flow routing models are produced by using the full continuity equation while eliminating some terms of the momentum equation. The simplest distributed model is the kinematic wave model, which neglects the local and convective acceleration, as well as the pressure terms. It assumes $S_o = S_f$. The diffusive wave model neglects the local and convective acceleration terms only, while the dynamic wave model considers all the terms in the momentum equation.

The kinematic wave model is used as an example for distributed flow models. If the momentum equation in the model is expressed by:

$$A = \alpha Q^\beta \quad (13)$$

and Manning's equation is used to express the flow, the kinematic wave model equations can be reduced to:

$$\frac{\partial Q}{\partial x} + \alpha \beta Q^{\beta-1} \left(\frac{\partial Q}{\partial t} \right) = q \quad (14)$$

where α is a function of roughness n , perimeter P , and bed slope S_0 , while β equals 0.6. The solution of kinematic wave model may be obtained numerically by using finite difference approximations to eqn (14) or analytically by solving the characteristic equations of the kinematic waves, which are two ordinary differential equations mathematically equivalent to the continuity and momentum equations (7). The kinematic wave method, which is mainly used for river routing, can be used also for catchment routing, where the lateral flow is equal to the difference between the rates of rainfall and infiltration, and the channel flow is taken to be flow per unit width of plane. A general kinematic wave algorithm has been developed (10), where several common routing methods are shown to be special cases of the algorithm.

COMPUTATIONAL EXPERIMENTS

The use of spreadsheets to perform flow routing computations is shown in the following examples. The examples include all the routing procedures described above. The tables showing the spreadsheet solution are arranged to explain the details of the spreadsheet design. The contents of selected cells are displayed to show the mathematical formulas used in the calculations. Row and column headings are displayed to help in understanding the formulas in the cells. Also, graphs of the input and output hydrographs are shown. The model input parameters can be changed to study their effect on the model output. The model responds to such changes instantly and both the outflow and the graph are updated accordingly. One of the spreadsheet advantages is the ability to carry out such 'what if' analysis efficiently. Different systems of units are used to be able to compare the results obtained with those reported in the references from which the examples were extracted (6,8). The examples are grouped under the three types of routing: reservoir, river and catchment routing, and two examples are given for each type. The examples cited below are meant to be simple in order to demonstrate the spreadsheet calculation procedure.

Flow Routing Calculations for Water Resources Management.....

Reservoir Routing

The first example demonstrates the solution of the level pool routing using the storage indication method. Table (1) shows how the spreadsheet is arranged, where the input data are the storage discharge relationship, and the inflow hydrograph. The storage-outflow function is calculated in column C as $(2S/\Delta t)+Q$. Column E calculates the slope of the function to be used for linear interpolation. Column L calculates the outflow by looking up the table relating storage-outflow function with Q given in the range C5:D9. The second example demonstrates the level pool routing procedure using the Runge Kutta method. Table (2) shows the calculation of the head increments and the depth which is used to calculate the outflow from the elevation outflow data given in the range J3:K23. It can be noticed from the graphs in Tables (1) and (2) that the peak flow occurs at the point of maximum storage, when the outflow hydrograph intersects the inflow hydrograph, since the maximum storage occurs when $dS/dt = I - Q = 0$.

River Routing

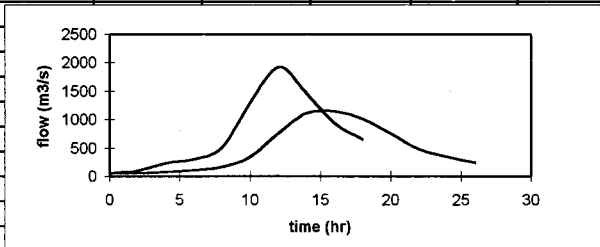
The third example demonstrates the calculations for the Muskingum method for river routing. Table (3) gives the details of calculations and the graph shows how the inflow hydrograph is routed through the channel. The input data are the values of K, X and Δt , from which the values of the constants C1, C2, and C3 are calculated in column F. The fourth example demonstrates another river routing procedure using the numerical solution of the kinematic wave. The hydraulic routing procedure as shown in Table (4) gives the values of flow as a function of both time and location. A backward-difference method is used to express eqn (14) in finite difference form. The calculation of the flow values is shown by the content of cell D14. The graph shows the propagation of the inflow hydrograph along the channel.

Catchment Routing

The fifth example explains how the flow through a series of linear reservoirs can be simulated using the analytical solution given by eqn (10). The input to the problem is the number of reservoirs n, the value of k, and

Table 1. Reservoir Routing by the Storage-Indication Method

	A	B	C	D	E	F	G	H	I	J	K	L
1		delt	120	min								
2												
3		Storage	S/O func	Discharge	slope		time	inflow	l _j +l _(j+1)	2S _j /delt-Q _j	S/O fun	Outflow
4		M m3	m3/s	m3/s			(hr)	m3/s	m3/s	m3/s	m3/s	m3/s
5		75	20890	57	0.0926		0	60		20776	20890	57
6		81	22727	227	0.1392		2	100	160	20814	20936	61
7		88	24825	519	0.1893		4	232	332	20985	21146	81
8		100	29108	1330	0.2491		6	300	532	21287	21517	115
9		110	32881	2270	0.0690		8	520	820	21767	22107	170
10							10	1310	1830	22901	23597	348
11							12	1930	3240	24605	26141	768
12							14	1460	3390	25756	27995	1119
13							16	930	2390	25850	28146	1148
14							18	650	1580	25406	27430	1012
15							20		650	24551	26056	752
16							22		0	23589	24551	481
17							24		0	22895	23589	347
18							26		0	22394	22895	250
19												
20												
21												
22												
23	Cell C6	2*B6*1000000/\$C\$3/60+D6										
24	Cell K6	J5+I6										
25	Cell L7	VLOOKUP(K7,\$C\$5:\$E\$9;2)+VLOOKUP(K7,\$C\$5:\$E\$9;3)*(K7-VLOOKUP(K7,\$C\$5:\$E\$9;1))										
26												

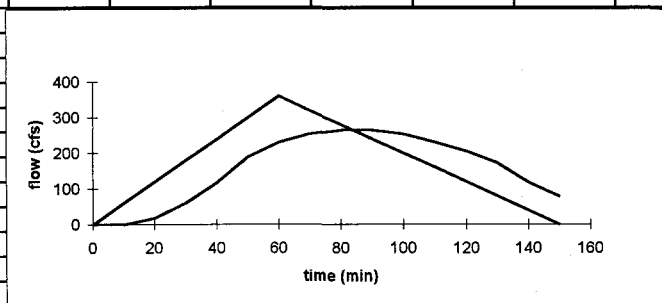


116

Aly N. El-Bahrawy

Table 2. Reservoir Routing by the Runge Kutta Method

	A	B	C	D	E	F	G	H	I	J	K	
1	time	inflow	delH1	delH2	delH3	delH	depth	outflow		elev	outflow	
2	(min)	(cfs)	(ft)	(ft)	(ft)	(ft)	(ft)	(cfs)		(ft)	(cfs)	
3	0	0					0	0		0.0	0	
4	10	60	0.00	0.28	0.55	0.41	0.41	0		0.5	3	
5	20	120	0.83	1.06	1.27	1.16	1.57	17		1.0	8	
6	30	180	1.42	1.52	1.61	1.56	3.13	60		1.5	17	
7	40	240	1.65	1.68	1.69	1.68	4.82	117		2.0	30	
8	50	300	1.69	1.69	1.71	1.70	6.52	190		2.5	43	
9	60	360	1.52	1.58	1.68	1.64	8.16	231		3.0	60	
10	70	320	1.78	1.44	1.11	1.27	9.44	253		3.5	78	
11	80	280	0.92	0.59	0.40	0.53	9.97	264		4.0	97	
12	90	240	0.22	-0.11	-0.15	-0.06	9.91	264		4.5	117	
13	100	200	-0.33	-0.51	-0.70	-0.61	9.31	253		5.0	137	
14	110	160	-0.73	-0.91	-0.95	-0.89	8.42	231		5.5	156	
15	120	120	-0.98	-1.16	-1.17	-1.12	7.30	205		6.0	173	
16	130	80	-1.17	-1.15	-1.33	-1.29	6.01	173		6.5	190	
17	140	40	-1.28	-1.23	-1.15	-1.18	4.82	117		7.0	205	
18	150	0	-1.06	-0.97	-1.15	-1.13	3.69	78		7.5	218	
19										8.0	231	
20										8.5	242	
21										9.0	253	
22										9.5	264	
23										10.0	275	
24												
25												
26												
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30												
31												
32												
33												
34	Cell C5	$(B4-VLOOKUP(G4;J$3:K$23;2))/43560*600$							Cell F5	$C5/4+3/4*E5$		
35	Cell D6	$(B5+(B6-B5)/3-VLOOKUP(G5+C6/3;J$3:K$23;2))/43560*600$							Cell G6	$G5+F6$		
36	Cell E7	$(B6+(B7-B6)*2/3-VLOOKUP(G6+D7*2/3;J$3:K$23;2))/43560*600$							Cell H7	$VLOOKUP(G7;J$3:K$22;2)$		
37												



Flow Routing Calculations for Water Resources Management.....

Aly N. El-Bahrawy

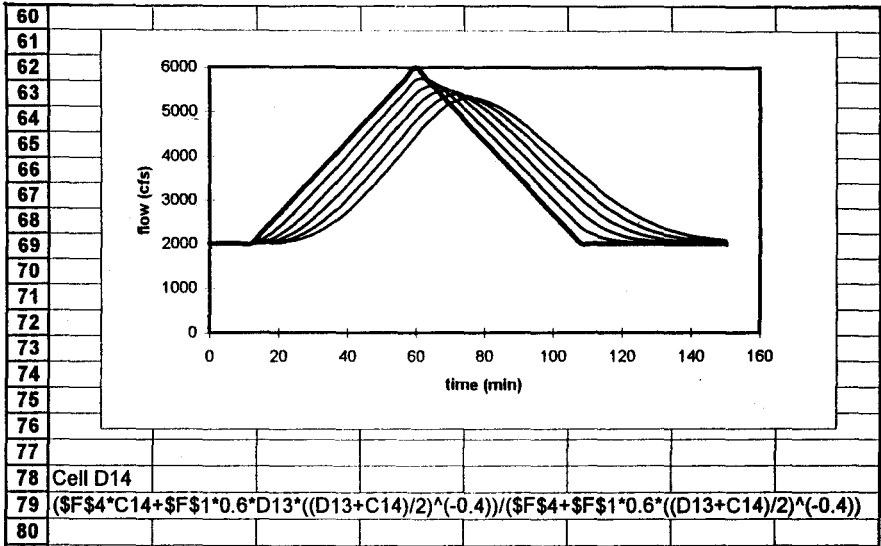
Table 3. River Routing by the Muskingum Method

	A	B	C	D	E	F
1	K	0.75	hr		C1	0.076923
2	X	0.25			C2	0.538462
3	delt	0.5	hr		C3	0.384615
4					sumC	1
5						
6	Time	Inflow	C1 I _{j+1}	C2 I _j	C3 Q _j	outflow
7	(hr)	(cfs)				(cfs)
8	0.0	819				739
9	0.5	1012	78	441	284	803
10	1.0	1244	96	545	309	949
11	1.5	1537	118	670	365	1153
12	2.0	1948	150	828	444	1421
13	2.5	2600	200	1049	547	1795
14	3.0	5769	444	1400	691	2534
15	3.5	12866	990	3106	975	5071
16	4.0	17929	1379	6928	1950	10257
17	4.5	20841	1603	9654	3945	15202
18	5.0	21035	1618	11222	5847	18687
19	5.5	20557	1581	11327	7187	20095
20	6.0	19485	1499	11069	7729	20297
21	6.5	14577	1121	10492	7807	19420
22	7.0	9810	755	7849	7469	16073
23	7.5	6448	496	5282	6182	11960
24	8.0	4558	351	3472	4600	8423
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39						
40	Cell F1	$(B3-2*B1*B2)/(2*B1*(1-B2)+B3)$				
41	Cell F2	$(B3+2*B1*B2)/(2*B1*(1-B2)+B3)$				
42	Cell F3	$(2*B1*(1-B2)-B3)/(2*B1*(1-B2)+B3)$				
43						

Flow Routing Calculations for Water Resources Management.....

Table 4. River Routing by the Kinematic Wave Method

	A	B	C	D	E	F	G	H
1		width	200	ft	α	3.49		
2		slope	0.01		delt	180	s	
3		n	0.035		delx	3000	ft	
4		length	15000	ft	delt/delx	0.06		
5								
6	Time	distance	0	3000	6000	9000	12000	15000
7	min	j/l	1	2	3	4	5	6
8	0	1	2000	2000	2000	2000	2000	2000
9	3	2	2000	2000	2000	2000	2000	2000
10	6	3	2000	2000	2000	2000	2000	2000
11	9	4	2000	2000	2000	2000	2000	2000
12	12	5	2000	2000	2000	2000	2000	2000
13	15	6	2250	2095	2036	2013	2005	2002
14	18	7	2500	2252	2118	2053	2023	2010
15	21	8	2750	2449	2246	2127	2062	2030
16	24	9	3000	2672	2414	2238	2129	2067
17	27	10	3250	2910	2613	2385	2228	2129
18	30	11	3500	3158	2836	2566	2360	2218
19	33	12	3750	3411	3076	2774	2525	2338
20	36	13	4000	3666	3327	3003	2719	2489



Aly N. El-Bahrawy

the time increment Δt . Table (5) gives the details of calculations, where the unit hydrograph is calculated in column B, and the convoluted outflow hydrograph is given in column H. More details on unit hydrograph routing using spreadsheets are given in (5). The graph shows the incremental responses and the total outflow hydrograph. Table (6) solves the same problem using a numerical solution similar to the one used for the Muskingum method, where the output from the j reservoir is used as input to the $j+1$ reservoir. The graph shows the output hydrographs from the three reservoirs. Figure (1) shows a comparison between the analytical and numerical routing.

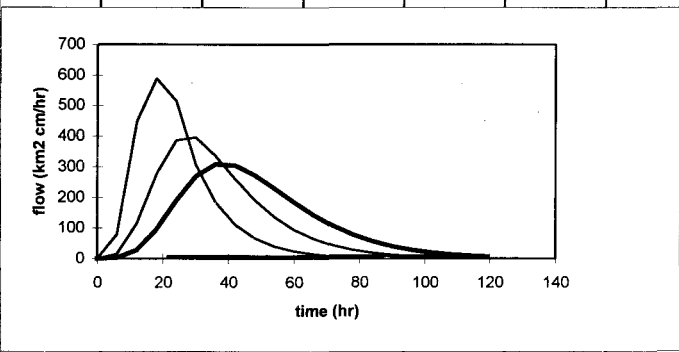
Table 5. Catchment Routing by Cascade of Linear Reservoirs (Analytical)

	A	B	C	D	E	F	G	H
1	n	3			Area	1000	km ²	
2	k	12	hr					
3								
4	Time	U(t)	rainfall	Q1	Q2	Q3	Q4	Qt
5	(hr)	(1/hr)	(cm)	km ² cm/hr				
6	0	0	0	0.00				0.00
7	6	0.00632	1.2	7.58	0.00			7.58
8	12	0.01533	6	18.39	37.91	0.00		56.30
9	18	0.02092	4.8	25.10	91.97	30.33	0.00	147.40
10	24	0.02256	2.4	27.07	125.51	73.58	15.16	241.32
11	30	0.02138		25.65	135.34	100.41	36.79	298.18
12	36	0.01867		22.40	128.26	108.27	50.20	309.13
13	42	0.01541		18.50	112.02	102.61	54.13	287.26
14	48	0.01221		14.65	92.48	89.62	51.30	248.05
15	54	0.00937		11.25	73.26	73.98	44.81	203.30
16	60	0.00702		8.42	56.24	58.61	36.99	160.26
17	66	0.00515		6.18	42.11	44.99	29.31	122.59
18	72	0.00372		4.46	30.91	33.69	22.50	91.55
19	78	0.00265		3.18	22.31	24.72	16.84	67.05
20	84	0.00186		2.23	15.88	17.85	12.36	48.32
21	90	0.00130		1.56	11.17	12.70	8.92	34.35
22	96	0.00089		1.07	7.78	8.94	6.35	24.14
23	102	0.00061		0.74	5.37	6.22	4.47	16.79
24	108	0.00042		0.50	3.68	4.29	3.11	11.58
25	114	0.00028		0.34	2.50	2.94	2.15	7.92
26	120	0.00019		0.23	1.69	2.00	1.47	5.39
27								
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43								
44	Cell B7	$1/(\$B\$2*FACT(\$B\$1-1))*(\$A7/\$B\$2)^{(\$B\$1-1)}*EXP(-A7/\$B\$2)$						
45	Cell D8	$\$C\$7*\$B8*1000$						
46								

Flow Routing Calculations for Water Resources Management.....

Table 6. Catchment Routing by Cascade of Linear Reservoirs (Numerical)

	A	B	C	D	E	F	G	H
1	n	3		delt	6	hr	C1	0.2
2	k	12	hr	C	0.5		C2	0.6
3								
4		n=1		n=2		n=3		
5		km2 cm/hr						
6	time	I1	Q1	I2	Q2	I3	Q3	
7	0	0	0		0		0	
8	6	200	80.0	40.0	16.0	8.0	3.2	
9	12	1000	448.0	264.0	115.2	65.6	28.2	
10	18	800	588.8	518.4	276.5	195.8	95.2	
11	24	400	513.3	551.0	386.3	331.4	189.7	
12	30		308.0	410.6	396.0	391.2	270.3	
13	36		184.8	246.4	336.2	366.1	308.6	
14	42		110.9	147.8	260.8	298.5	304.6	
15	48		66.5	88.7	192.0	226.4	273.3	
16	54		39.9	53.2	136.5	164.2	229.7	
17	60		23.9	31.9	94.7	115.6	184.0	
18	66		14.4	19.2	64.5	79.6	142.2	
19	72		8.6	11.5	43.3	53.9	106.9	
20	78		5.2	6.9	28.7	36.0	78.5	
21	84		3.1	4.1	18.9	23.8	56.6	
22	90		1.9	2.5	12.3	15.6	40.2	
23	96		1.1	1.5	8.0	10.2	28.2	
24	102		0.7	0.9	5.2	6.6	19.5	
25	108		0.4	0.5	3.3	4.2	13.4	
26	114		0.2	0.3	2.1	2.7	9.1	
27	120		0.1	0.2	1.3	1.7	6.2	
28			0.1	0.1	0.9	1.1	4.1	
29								
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43								
44								
45								
46								
47	Cell C10	2*\$H\$1*B10+\$H\$2*C9					Cell E2	E1/B2
48	Cell D11	AVERAGE(C10:C11)					Cell H1	E2/(2+E2)
49							Cell H2	(2-E2)/(2+E2)
50								



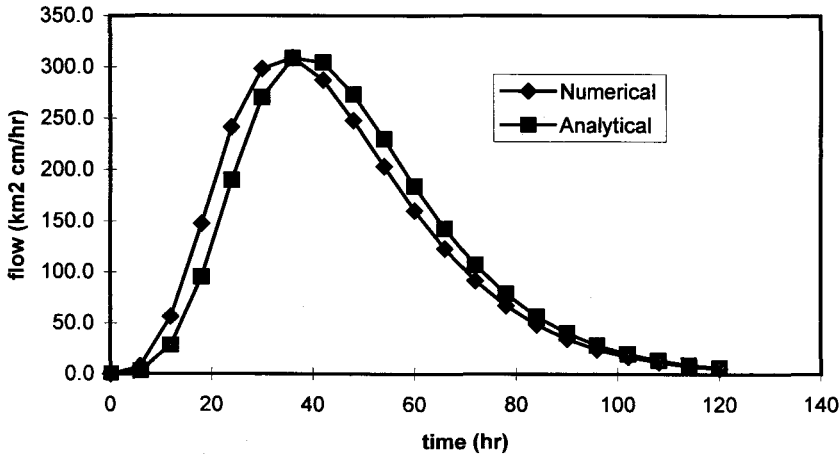


Fig. 1. Comparison between analytical and numerical catchment routing

DISCUSSION AND CONCLUSIONS

The above computational experiments demonstrate how different routing procedures can be easily and efficiently programmed using spreadsheets. Other routing methods not included in the paper can be programmed similarly. The inherent nature of routing calculations suits the arrangement of variables in columns and cells, which facilitates the development of the calculation formulas. All the models developed can work as templates for other examples with different input and system of units, with very minor changes. Although the spreadsheet models are easy to grasp, they may be used for design by engineers with no spreadsheet experience, where only the input cells can be changed by the user, while the calculation cells are protected against accidental change. Also, the models can serve as useful educational modules for the subject of computational hydrology. The produced outputs of the spreadsheet models can readily be included in reports or presentations, and the options available allow the user to further improve the appearance of results. The produced graphs are very useful for testing the routing procedure and assessing the relative importance of input parameters in case of model calibration.

Flow Routing Calculations for Water Resources Management.....

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