Channel Routing with Flow Losses

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Abstract: A technique is developed and implemented within the NWS FLDWAV model to account for the effect of flow-volume losses in one-dimensional (1D) open-channel unsteady flow modeling. A functional form for the loss-induced lateral outflow is derived based on a specified total-volume distribution along the reach in which the loss occurs. The flow-loss–enhanced FLDWAV model is capable of modeling unsteady flow with any specified amount of flow loss between any two cross sections along the routing reach.

INTRODUCTION

In distributed dynamic channel-flow routing, the unsteady flow properties are obtained by numerically solving the complete differential equations of one-dimensional (1D) unsteady flow (the Saint-Venant equations). These equations represent the conservation of the fluid mass and momentum, and a good numerical model, such as the weighted four-point implicit finite-difference solution used in the NWS FLDWAV model, should preserve the basic conservation feature. A simple check of the mass conservation is that the computed total-flow volume passing through any two cross sections along the routing reach is the same, if there is either no lateral inflow or outflow between the two cross sections during the routing or the routing begins from a steady state and returns to the same state at the end time of the routing. Sometimes in practical unsteady flow modeling, it is necessary to consider the effect of actual flow losses. Often in the case of dam-break floods, where the extreme high flows inundate considerable portions of the overbank or floodplain, a measurable loss of flow volume occurs. This loss is due to infiltration into relatively dry overbank material and flood-detention storage losses due to topographic depressions and/or water trapped behind agricultural irrigation levees. In channel routing, sometimes an increase in flow volume also needs to be considered when substantial precipitation exists in the routing reach. This total volume loss or gain can be taken into account by adding an extra lateral-outflow term in the continuity equation of the Saint-Venant equations. In the NWS DAMBRK model (Fread 1991), this loss-induced lateral outflow is determined by estimating a local peak discharge and computing an averaged outflow rate. A new technique for determining the loss-induced lateral outflow within the NWS FLDWAV model is developed, described, and test results are presented. This technique is based on an analytical derivation of the loss-induced lateral outflow and is capable of modeling any amount of specified loss for any part of the entire routing reach. It is found that the new method provides improved performance and more flexible applicability.

FORMULATION

If an unsteady flow is routed through a channel reach L and there is a flow loss during the routing period between $x = x_1$ and $x = x_2$ within the entire routing reach L, the result of this flow loss is a decrease in the total flow volume passing the two locations, i.e.

$$\int_{t_1}^{t_2} Q(x_1, t)\, dt > \int_{t_1}^{t_2} Q(x_2, t)\, dt \tag{1}$$

where $Q(x, t)$ = discharge; and t_1 and t_2 = beginning and ending times of the routing period. At each of these times, the flow magnitude is assumed to be at the same steady state, as shown in Fig. 1. The flow loss can be measured in terms of a total active volume, QV, which is the difference between total flow volume and the volume of base flow, i.e.

$$QV(x) = \int_{t_1}^{t_2} [Q(x, t) - Q_b]\, dt \tag{2}$$

where Q_b = base steady-flow discharge at the beginning and ending of the routing period. The ratio of volume loss to the total active flow volume can be represented as α, i.e.

$$\alpha = [QV(x_2) - QV(x_1)]/QV(x_1) \tag{3}$$

which is, in effect, a flow-loss (negative) or gain (positive) factor. Since the value of the factor cannot be determined in advance of a flood event, a set of different values can be used for the routing, and the computational results can be compared to evaluate the effects duo to the flow loss or gain.

The effects of the flow loss to the unsteady-flow simulation can be determined by adding an additional lateral-flow term to the continuity equation of the Saint-Venant equations, i.e.

$$\frac{\partial Q}{\partial x} + \frac{\partial (A + A_0)}{\partial t} - q_l = 0 \tag{4}$$

where A = active cross-sectional area; A_0 = inactive (off-channel storage) cross-sectional area; q_l = additional lateral flow due to the induced flow-volume loss. It is assumed that there is no natural inflow or outflow along the routing reach in this situation.

Two assumptions are made to determine the loss-induced lateral flow, $q_l(x, t)$. The first assumption is that the loss-in-

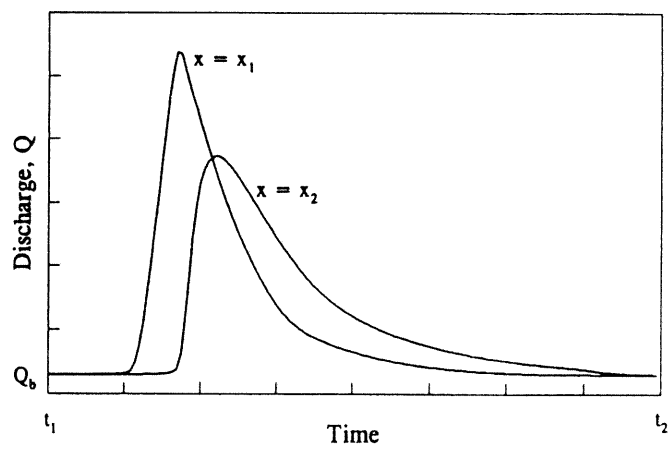

FIG. 1. Discharge Hydrographs

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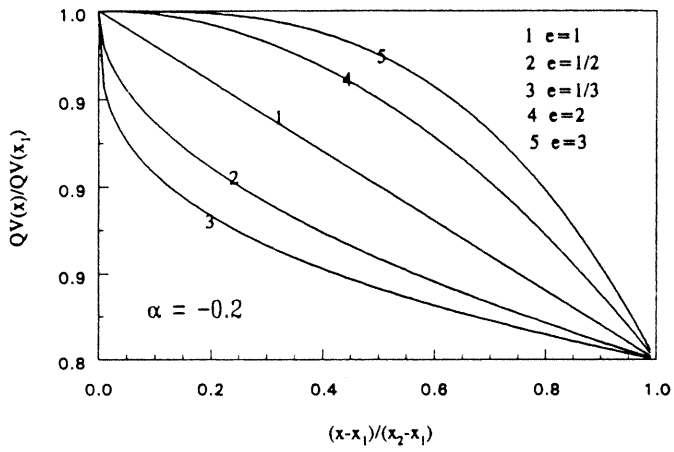

FIG. 2. Change of Total Active Volume, $QV(x)$

duced lateral flow is proportional with the local flow rate and its duration as

$$q_1(x, t) = \left[\frac{Q(x, t) - Q_b}{Q_m(x) - Q_b}\right] q_{1m}(x) \tag{5}$$

where $Q_m(x)$ = unknown local peak discharge; and $q_{1m}(x)$ = unknown local maximum lateral flow due to the loss. The second assumption is that the change of total active volume, $QV(x)$, due to the loss between the two locations $x = x_1$ and $x = x_2$ can be expressed as

$$QV(x) = QV(x_1)\left[1 + \left(\frac{x - x_1}{x_2 - x_1}\right)^e \alpha\right] \tag{6}$$

where e = parameter specifying the pattern of the change of the total active volume. Some functions of $QV(x)$ with $\alpha = -0.2$ for different values of e are shown in Fig. 2; a value of $e = 1$ results in a simple linear decrease in the total active volume from $QV(x_1)$ to $(1 + \alpha)QV(x_1)$.

Combining the (4) and (5) and integrating it for the time from t_1 to t_2 leads to

$$\int_{t_1}^{t_2} \frac{\partial(Q - Q_b)}{\partial x} dt + \int_{t_1}^{t_2} \frac{\partial(A + A_0)}{\partial t} dt - \int_{t_1}^{t_2} q_{1m}\left(\frac{Q - Q_b}{Q_m - Q_b}\right) dt = 0 \tag{7}$$

Since the flow is in the same steady state at $t = t_1$ and $t = t_2$, the second term on the left side of (7) is zero. Eq. (7) can be written as

$$\frac{\partial QV(x)}{\partial x} - \beta(x)QV(x) = 0 \tag{8}$$

where $\beta(x) = q_{1m}(x)/[Q_m(x) - Q_b]$. Combining (8) and (6) results in an analytical solution of $\beta(x)$, or finally, the loss-induced lateral flow, $q_1(x, t)$, as

$$q_1(x, t) = \frac{e(x - x_1/x_2 - x_1)^{e-1}\alpha[Q(x, t) - Q_b]}{[1 + (x - x_1/x_2 - x_1)^e\alpha](x_2 - x_1)} \tag{9}$$

The analytical equation in (9), determines the loss-induced lateral flow as a function of local discharge for any specified amount of loss, α, between any two cross sections x_1 and x_2 along the routing reach. Using (9) for q_i in (4), the NWS FLDWAV model is capable of modeling unsteady flows with specified flow losses or gains.

RESULTS

Some numerical tests are made to test the model performance for taking into account the flow loss or gain. The technique is also applied to a real dam-break simulation where a measurable flow-volume loss was observed.

Fig. 3 shows some computed flood-peak profiles for a testing situation in which a flood wave with a time of rise of 0.5 h and a peak discharge of 1,700 m^3/s (60,000 cfs) passing through a 16.09 km (10 mile) rectangular channel with a width of 61 m (200 ft), a slope of 0.00038 (2 ft/mi), and Manning's n of 0.03. The flood is routed under three conditions: (1) without flow loss, (2) with 15% total active flow-volume loss along the entire routing reach, and (3) with 15% total active flow-volume gain. For the first condition, it is found that the difference of computed total active flow volumes between $x = 0$ and $x = 16.09$ km is only -0.2%. This fairly small difference in computed total volumes indicates that the combined numerical errors are small and the FLDWAV model preserves the mass conservation quite well in this situation. For second and third conditions, a value of $e = 1.0$ in (6) is used, and the computed total flow-volume changes are -15.2% and $+13.9\%$, which are quite near the desired changes. Fig. 3 compares the compared flood-peak discharge profiles for these three conditions, and it can be seen that the flood-wave attenuation is influenced by the flow loss or gain.

The parameter e in (6) assumes the manner in which the total flow volume changes from x_1 to x_2. The effects of the e value on the computational results are examined. Fig. 4 shows the computed peak discharge profiles from three e values for a 20% flow-loss condition. Compared with the peak profile from $e = 1.0$, the other two values of e produce a difference of less than 3%, which suggests that a simple linear change assumption ($e = 1.0$) is acceptable.

This technique for simulating the effects of flow losses is applied to a historical dam-break flood simulation. Teton Dam, an earth-fill dam, 93 m (305 feet) high and with a 915 m

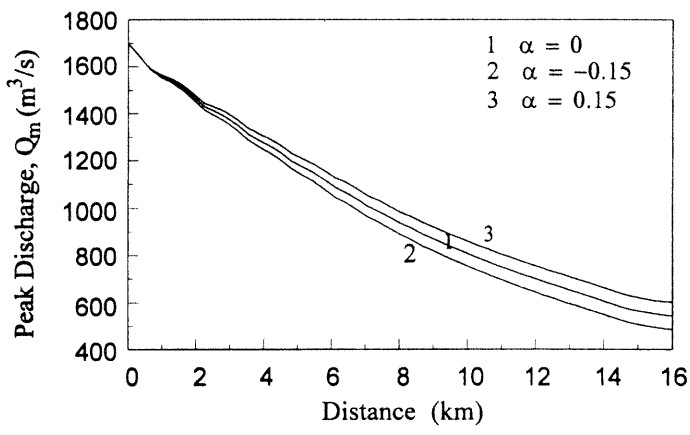

FIG. 3. Peak Discharge Profiles (e = 1.0)

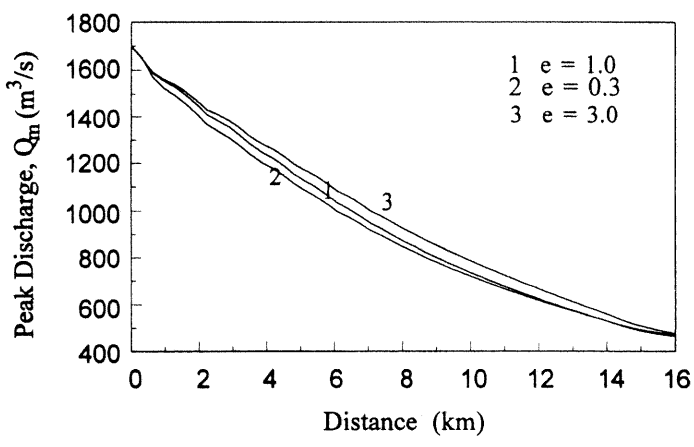

FIG. 4. Peak Discharge Profiles (α = −0.2)

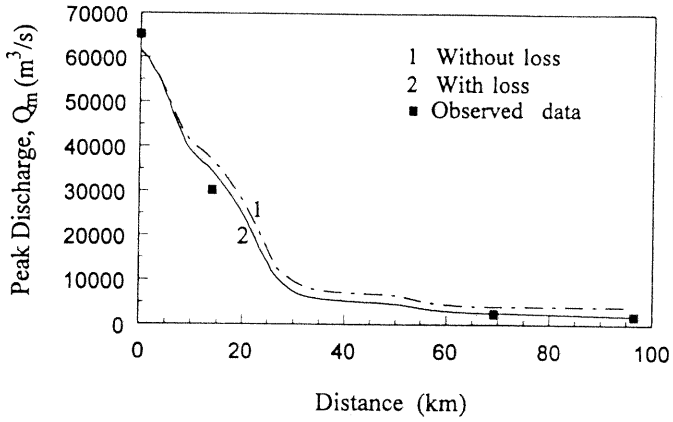

FIG. 5. Peak Discharge of Teton Dam

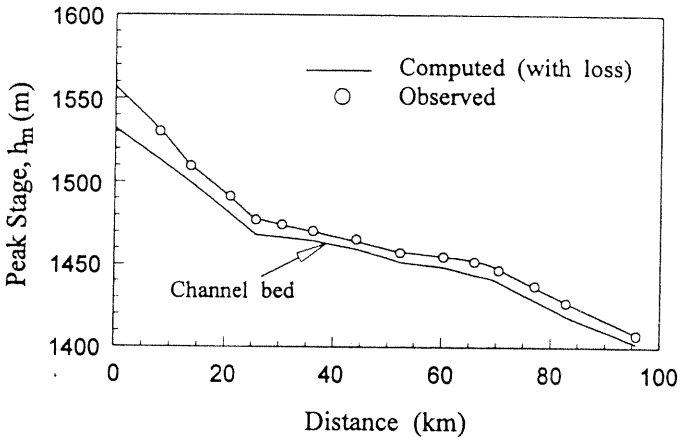

FIG. 6. Peak Stage of Teton Dam

(3,000 ft) long crest located on the Teton River in southeastern Idaho, failed on June 5, 1976 and caused the loss of lives and great damages. Data from the U.S. Geological Survey provided observations on the approximate development of the breach; description of the reservoir storage, downstream cross sections, and estimated values of Manning's resistance coefficients approximately every 8 km (5 mi), indirect peak discharge measurement, flood-peak travel times, and flood-peak stages at some locations are available. A characteristic feature of the dam-break flood from the Teton Dam failure is that a large amount of flow-volume loss was observed amounting to an estimated 30% of the total volume. Fig. 5, Fig. 6, and Table 1 present some computational results from the FLDWAV model. For the simulation run with flow loss, the loss-related inputs are $e = 1.0$ and $\alpha = -0.5$ (35% of total loss). The comparison between the results with and without this loss shows that the model produced much better computational results with the flow loss taken into account, and the technique for flow loss performed very well in this real dam-break situation. Comparing this method with the one used in the NWS DAMBRK model, the new technique performs better in retaining the desired flow-volume loss, and it provides greater flexibility for taking losses or gains for any portion along the routing reach since the DAMBRK method can only simulate the losses between the dam and downstream boundary. Also, the new method does not require iterative applications as required by the DAMBRK method. In the Teton flood simulations, the two methods produced similar results for the peak stages and flows.

TABLE 1. Errors of Computed Peak Stage for Teton Dam

$n = 14$ (1)	With loss (2)	Without loss (3)
$\sum_{i=1}^{n} (\Delta h)_i/n$	−0.24	2.38
$\sum_{i=1}^{n} \lvert\Delta h\rvert_i/n$	1.63	3.07
$\sqrt{\sum_{i=1}^{n} (\Delta h)_i^2/n}$	1.97	4.08

CONCLUSION

In modeling unsteady flows, it is sometimes necessary to consider the effect of a specified flow-volume loss or gain along a certain portion of the routing reach. The flow loss can be taken into account by adding an additional lateral-flow term to the Saint-Venant equations. This paper has proposed a technique to determine the flow-loss–induced lateral flow. A functional form for the flow-loss–induced lateral flow is derived based on an assumption that the loss is proportional to the local flow rate and its duration, and on a specified distribution of the total-flow volume along the reach in which the loss occurs. A testing example and an application of historical dam-break flood simulation for Teton Dam where a large amount of flow-volume loss was reported has shown excellent performance of the technique. The technique provides the NWS FLDWAV model with a capability of considering any amount of flow-volume loss between any two cross sections along a routed reach.

APPENDIX. REFERENCES

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