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TRANSMISSION LOSSES, FLOOD PEAKS, AND GROUNDWATER RECHARGE

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Abstract

Abstractions of streamflow in ephemeral stream channels from infiltration in the channel beds and banks are called transmission losses. These losses are important because water is "lost" as flood waves travel through the normally dry channel networks. Thus, local aquifers are recharged and runoff volumes and flood peaks are reduced over what they would be in the absence of transmission losses. Stream channels crossing alluvial fans transport water from mountain fronts to lower portions of the watersheds. Although these channels are unstable and variable in time and space, they retain their ephemeral character and thus transmission losses can exhibit their influence on flood peaks, water yield, and groundwater recharge as described for ephemeral stream channel networks. Recently developed procedures to estimate transmission losses for individual flow events in ephemeral stream channels are described. Parameters of the transmission-loss model are determined, by calibration, using measured inflow and outflow volumes from gaged ephemeral stream channel segments. Data from 127 hydrographs on 10 channel reaches in Arizona, Kansas, Nebraska, and Texas are used to develop parameter estimation equations and tables of parameter values for the transmission-loss model. Example applications of the transmission-loss model in predicting flood frequency curves and in estimating potential groundwater recharge from transmission losses are described.

Introduction

In arid and semiarid regions, increasing populations, urbanization, expanding industry, and irrigated agriculture are increasing demand for water resources. This demand results in increasing competition for existing water supplies and pressure to develop new sources of water. The increased demand for water resources requires better methods of assessing streamflow and assessing the interaction between streamflow, flooding,

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infiltration losses in channel beds and banks, and groundwater recharge. Abstractions of streamflow in stream channel systems from infiltration in the channel beds and banks are called transmission losses.

Transmission losses are important because water is "lost" as flood waves travel through the normally dry stream channel systems or networks. Thus, runoff volumes and flood peaks are reduced over what they would be in the absence of transmission losses (e.g. see Babcock and Cushing, 1941 and Renard, 1970). Transmission losses are an important component of the water budget because surface water yields are reduced, riparian vegetation and wildlife are supported, and local aquifers are recharged (e.g. see Renard, 1970). Therefore, prediction of flood peaks and calculation of water budgets for watersheds in arid and semiarid areas require quantification of the impacts of transmission losses on components of the hydrologic cycle.

As stream channels traversing alluvial fans transport water from mountain fronts to lower portions of the watersheds, significant flow occurs in channels incised into the alluvium forming the fan (Goudie and Wilkinson, 1977). Although these channels are unstable and variable in time and space, they retain their ephemeral character and thus transmission losses can exhibit their influence on flood peaks, water yield, and groundwater recharge as described for ephemeral stream channel networks.

In terms of flood routing and transmission losses, the main differences between ephemeral stream channel networks forming the drainage pattern in watersheds and ephemeral channel segments traversing alluvial fans are due to the nature of their structure and linkage. Channel systems in watersheds tend to be dendritic in structure with main channels collecting tributary inflow in the downstream direction. Channel segments on alluvial fans tend to be singular or bifurcating in the downstream direction. Usually there is no tributary inflow but channels can split or diverge resulting in tributary outflow in the downstream direction. In spite of these differences, many of the same flow processes occur in watersheds and on alluvial fans and procedures developed to consider streamflow and transmission losses by individual stream channel segment can be applied to either system.

Overview of the Model

Procedures have been developed to estimate transmission losses for individual flow events in ephemeral stream channels (Lane, 1982 and Lane, 1985). The rate of change of runoff volume with distance downstream in an ephemeral stream channel segment subject to transmission losses is described by a first order differential equation. The differential equation assumes the volume of losses in a reach is proportional to the volume of upstream inflow, a constant or steady-state loss rate, and the rate of lateral inflow per unit length of channel.

In equation form,

$$dV(x,w)/dx = - wc - wkV(x,w) + V_L/x \quad (1)$$

where: $V(x,w)$ is the volume of flow (acre-ft or m^3) in a channel segment of length x (ft or m) and mean width w (ft or m), V_L is the volume of lateral inflow (assumed uniform along the reach) in the same units at $V(x,w)$, and c and k are parameters. The solution to Eq. (1) is:

$$V(x,w) = a(x,w) + b(x,w)V_u + F(x,w)V_L/x \quad (2)$$

where: $V(x,w) \geq 0$ is the outflow volume in acre-ft or m^3, V_u is the upstream inflow volume in the same units, and $a(x,w)$, $b(x,w)$, and $F(x,w)$ are functions described below. Notice that in the absence of lateral inflow, the upstream inflow V_u must be larger than $-a(x,w)/b(x,w)$ or all the inflow is lost in the channel segment and $V(x,w) = 0$. If there is lateral inflow then there will always be some outflow and $V(x,w)$ will be greater than zero.

To calculate the volume of transmission losses in a channel segment rather than the volume of outflow, the volume of transmission losses is computed as the sum of the upstream and lateral inflow volumes minus the outflow volume. In equation form:

$$TL(x,w) = V_u + V_L - [a(x,w) + b(x,w)V_u + F(x,w)V_L/x] \quad (3)$$

where $TL(x,w)$ is the volume of transmission losses in the segment in the same units as $V(x,w)$.

The relationships between the functions and the parameters c and k are:

$$a(x,w) = [a/(1-b)][1 - b(x,w)] \quad (4)$$

$$b(x,w) = \exp(-kxw) \quad (5)$$

$$F(x,w) = [1 - b(x,w)]/(kw) \quad (6)$$

and

$$c = -ka/(1-b) \quad (7)$$

Values of a, k, and b have been related to the effective, steady-state hydraulic conductivity K (in/h or mm/h), the mean duration of inflow to the reach D (h), and the mean volume of inflow to the reach V (acre-ft or m^3) (Lane, 1982) in English units as:

$$a = -0.00465\ KD \quad (8)$$

$$k = -1.09\mathrm{Log}_e(1 - 0.00545KD/V) \quad (9)$$

and

$$b = \exp(-k) \tag{10}$$

Earlier analyses (Murphey, and others, 1977) of data from experimental watersheds in southeastern Arizona produced a statistical estimation equation for the mean duration of flow as

$$D = C_1A^{C2} = 2.53A^{0.2} \tag{11}$$

with $R^2 = 0.78$ and A as the watershed area in sq mi. A similar equation for the mean volume of flow is

$$V_{in} = C_3A^{C4} = 0.05A^{-0.2} \tag{12}$$

with $R^2 = 0.61$, A as the watershed area in sq mi, and V_{in} is the mean volume of runoff in inches. Notice that V_{in} must be converted to V in acre-ft before it is used in Eq. (9).

Data Base Used for Calibration of the Model

The data base used to derive Eqs. (8) - (10) was taken from 10 gaged channel reaches in Arizona, Kansas, Nebraska, and Texas and represents 127 individual event hydrographs. Therefore, application of the transmission-loss model to streams in other areas is probably not warranted without local calibration data for a, k, b, D, and V in Eqs. (8) - (12).

The effective saturated conductivity, K, represents the steady-state conductivity of the channel bed material under field conditions of entrapped air and sediment laden flow. Therefore, it can be an order of magnitude less than conductivity estimates made with infiltrometers and clear water. Values of the effective conductivity were derived by taking the total losses from an event divided by the length and width of the segment and by the duration of flow. With proper units conversion, the result is an estimate of K in in/h for each flow event. These estimates were averaged over all flow events for a channel segment to derive an estimate of the mean effective hydraulic conductivity. Values of K for different bed material classes were tabulated by Lane (1982).

Example Application

Solutions to the differential equation for transmission losses with parameter values as described above account for empirically observed dependence of infiltration losses on rate of inflow to a channel reach and simulate reductions in flood peaks and volumes measured in ephemeral stream channel networks.

Estimated flood peaks from observed data and from applying a distributed watershed model incorporating the transmission-loss model are given in Table 1. These data represent 8 very small to small watersheds in southeastern Arizona.

Table 1. Comparison of estimated flood peaks derived from measured data and simulation results using a distributed watershed model (Lane, 1982; Lane 1985) incorporating the transmission loss model.

Watershed	Record Length (yr)	Area (sq mi)	Estimated Flood Peaks in cfs per sq mi 1,2			
			Observed		Simulated	
			2 yr	100 yr	2 yr	100 yr
Walnut Gulch, AZ						
63.103	17	.0142	620.	2960.	610.	3790.
63.104	17	.0175	710.	5160.	630.	3740.
63.111	20	.223	600.	3190.	370.	2230.
63.011	13	3.18	210.	2520.	230.	2890.
63.008	13	5.98	120.	1050.	140.	840.
Safford, AZ						
45.001	30	.81	100.	1240.	110.	1220.
Tucson, AZ						
High School Wash	8	.90	420.	1690.	300.	2150.
Big Wash	11	2.75	80.	2480.	270.	1520.

1. 1 cfs per sq mi - 0.0109 cms per sq km.
2. Log-normal probability distribution used to estimate flood frequency.

An important consequence of the transmission-loss model and simulation results summarized in Table 1 is a partial explanation of empirical observations of decreasing flood peaks and volumes with increasing drainage area on the Walnut Gulch Experimental Watershed (Keppel, 1960). Calculations with the simulation model with and without transmission losses suggest the following. For the 2 yr flood on watershed 63.103 (0.0142 sq mi), transmission losses reduced the peak discharge about 2%. But, the corresponding reduction for the 5.98 sq mi watershed 63.008 with an extensive channel system was estimated as about 30% in the peak discharge and runoff volume. It is estimated that on watershed 63.008 about 1/3 of the runoff volume from the 2 yr flood becomes transmission losses and thus potential groundwater recharge. The importance of recharge through the ephemeral stream channels on Walnut Gulch has been confirmed by increases in water levels in wells in and adjacent to the main channels following flood events (Wallace and Renard, 1967).

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