Ephemeral Channel Modelling at Historic timescales in Semi-arid Environments

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ABSTRACT

There is an increasing need to understand how ephemeral channels mediate the movement of water through catchment systems, both to identify the quantity of groundwater and reservoir recharge and to inform flash flood prediction. At historic timescales (10^1-10^2 years) it is recognised that this requires an understanding of the interactions between flow, sediment and vegetation which feedback to control morphological change and future flood wave propagation. Reduced-complexity models provide a means to develop such understanding. This paper presents a coupled 1D-2D numerical model that can be applied at the catchment scale to account for transmission losses and floodwave propagation (1D model), but which also simulates local-scale flow patterns that may be applied to simulate geomorphic response to flood inundation (2D model). The initial model evaluation, conducted at the Walnut Gulch Experimental Watershed, Arizona is presented.

INTRODUCTION

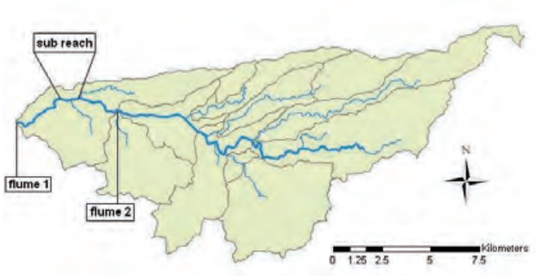
There is an increasing need to understand how ephemeral channels mediate the movement of water through catchment systems, both to identify the quantity of groundwater and reservoir recharge (Coes and Pool, 2005) and also to inform flash flood prediction. This knowledge is increasingly needed at historic timescales (10^1-10^2 years) as water is likely to remain a limited resource in response to climatic change in semi-arid environments (Ragab and Prudhomme, 2002). At this timescale, however, complex flow-sediment-vegetation interactions control morphological change which feeds back to control future flood wave propagation. It is increasingly recognised that an understanding of changes in discharge and flood inundation over historic timescales requires an understanding of the non-linear interactions between channel morphology and discharge (Goodrich *et al.*, 2008). Reduced-complexity models provide a means to develop this understanding. Such models must be capable of incorporating the effects on channel morphology of controls that operate at both the reach scale (e.g. local channelisation and bar formation in response to distributed flow patterns) and catchment scale (e.g. floodwave propagation, transmission losses) in a computationally efficient manner. Existing models tend to represent one or other scale of process controls, but not both. This paper presents initial investigations into the applicability of a coupled 1D-2D reduced complexity flow model to: First, simulate flood wave propagation and transmission losses at the Walnut Gulch Experimental Watershed; Second, predict distributed flow patterns in comparison with a two-dimensional depth-averaged solution to the shallow water equations.

METHOD

The 1-D component of the model routes discharge down stream between a series of cross sections using the one dimensional form of the kinematic wave equation. The Muskingum-Cunge method is used to solve the kinematic wave equation (Ponce and Lugo, 2001):

$$Q_{j+1}^{i+1} = C_0 Q_j^{i+1} + C_1 Q_j^i + C_2 Q_{j+1}^i + C_3 Q_l \quad (1)$$

where Q is discharge (m^3s^{-1}); Q_l is infiltration (m^3s^{-1}); *i* is the temporal index and *j* is the spatial index. C_n (n = 0-3) are routing coefficients. Infiltration is simulated with a bucket model; infiltration occurs in the reach between each cross section until a given capacity is reached, thereafter flow infiltrates at a steady state. The 1-D model was evaluated with three runoff events with negligible lateral inflow along a ~6.5km reach of the main channel of The Walnut Gulch Experimental Watershed, a 150km² experimental watershed located in south-east Arizona, U.S.A. The upstream hydrograph for each event was determined from the runoff record at flume 2. These data, alongside borehole measurements taken upstream of Flume 1 (Coes and Pool, 2005) were used to determine routing coefficients and infiltration parameters. No data on initial moisture content was available for each event. The purpose of this analysis is to evaluate whether the flow model coupled with the simple infiltration model is capable of capturing the shape of the downstream hydrograph, and therefore the timing and magnitude of at-a-point inundation. Initial moisture content was therefore adjusted to calibrate the total amount of infiltration for each event, and the output hydrograph evaluated in comparison to the observed downstream hydrograph at Flume 1.



Event	*E*	Moisture (m^3/m^3)
25/07/2007	0.89	0.16
10/08/2006	0.85	0.16
06/08/2007	0.96	0.23

Table 1. Nash-Sutcliffe Efficiency Statistics for three simulated hydrographs, and calibrated moisture content.

Figure 1. Walnut Gulch Experimental Watershed, showing the location of the upstream (Flume 2) and downstream (Flume 1) flumes for 1-D model evaluation, and the sub-reach location used for model inter-comparison.

The 2-D component of the model routes flow downstream through a Cartesian grid of cells based on discharge and water level calculations derived from the 1-D component of the model. The first stage in model implementation is to determine the relative downstream distance (R_i) for a given cell (*i*) in the grid from the reach inlet. Values of R_i are set equal to zero at cells along the upstream boundary and equal to one at cells along the downstream boundary; values of R_i along the reach are calculated iteratively by averaging the value of R_i at a given cell with those of neighbouring cells (see (Nicholas, 2009) for more detail). Values of R_i are then used to define cross-sections at regular distances downstream. Flow is routed downstream through the model grid in a two stage procedure. First, discharge is calculated at each cross section using the 1-D method as outlined above. The water level required to convey this discharge (*Q*) is then calculated iteratively using the Chezy equation to calculate unit discharge (q_i) in each distributed cell that constitutes the cross-section:

$$q_i = C h_i^{3/2} S^{1/2} \quad (2)$$

where *C* is the Chezy roughness coefficient, h_i is the flow depth at cell *i* and *S* is channel gradient. Second at the upstream end of the reach values of unit discharge (q_i) are converted into fractions of total discharge. Discharge fractions are then routed to neighbouring downstream cells using an iterative procedure:

$$q_{fij} = q_{fi} p_{ij} / \sum_{j=1}^{J} p_{ij} \quad (3)$$

where q_{fij} is the fraction of discharge routed from cell i to cell j, p_{ij} is the routing potential between these cells, and J is the total number of neighbouring downstream cells. The routing potential is calculated as follows:

$$p_{ij} = h_j^{3/2} Sw_{ij}^{1/2} \beta_j \tag{4}$$

where h_j is the depth of flow at the downstream cell (j), Sw_{ij} is the water surface slope between cells i and j, and $ß_j$ is a correction factor. Flow depth at each cell is calculated based on water surface elevations at the nearest upstream and downstream cross-sections, and the relative distance of the cell between these cross-sections. For the first iteration $ß_j$ is equal to unity. The correction factor is modified during subsequent iterations to minimise the energy slope at each cell with that of neighbouring cells (Nicholas, 2009).

The aim of the analysis presented here is to determine whether the reduced complexity flow model described above is capable of reproducing the distributed flow predictions of a more complex two-dimensional depth averaged shallow water equation model (DELFT3D-FLOW). Models comparison took place along a 900m sub-reach of the main channel at Walnut Gulch (Figure 1).

RESULTS AND DISCUSSION

The results presented in Table 1 and Figure 2 demonstrate that given appropriate data regarding the nature of the inflow hydrograph at Flume 2, the 1-D flow model is capable of simulating the observed hydrograph at Flume 1. The infiltration model, although simple, simulates higher rates of infiltration during the initial stages of the flow event, which are consistent with observations (Blasch, 2006) and lead to preservation of the output hydrograph. Initial moisture contents in the channel bed prior each event (Table 1) are within the observed range for the borehole upstream of flume 1 (Coes and Pool, 2005) and are consistent with the occurrence of runoff events in the days preceding each event. The simulated hydrographs have a slight tendency to over estimate both peak discharge and the rate of recession of the receding limb (Figure 2). This is a result of using constant routing parameters for each event. This issue may be addressed through a two-way coupling between 1-D and 2-D models.

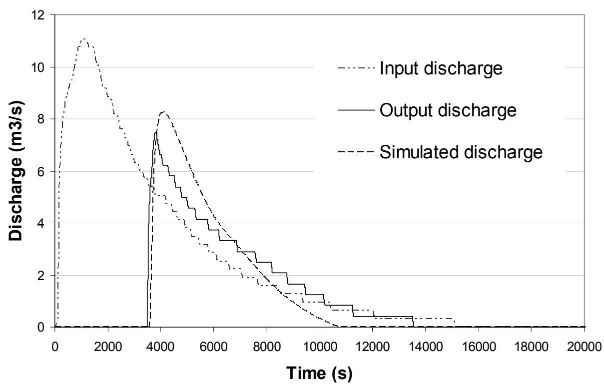


Figure 2. Observed and Simulated Hydrographs for the flow event on the 10/8/2006.

The coupled model described above reproduces patterns of unit discharge that are broadly similar to those derived from the shallow water equation model (Figure 3). In particular, the model is able to reproduce zones of higher unit discharge associated with local topographic forcing. The developed model tends to concentrate flow into narrower threads in response to local channel morphology (Figure 3); this tendency may partly reflect the insensitivity of the relative downstream distance (R_i) to local morphology (bars; emerged morphology). As noted previously however (Nicholas, 2009), the difference in model performance may also reflect numerical diffusion in the shallow water equation model.

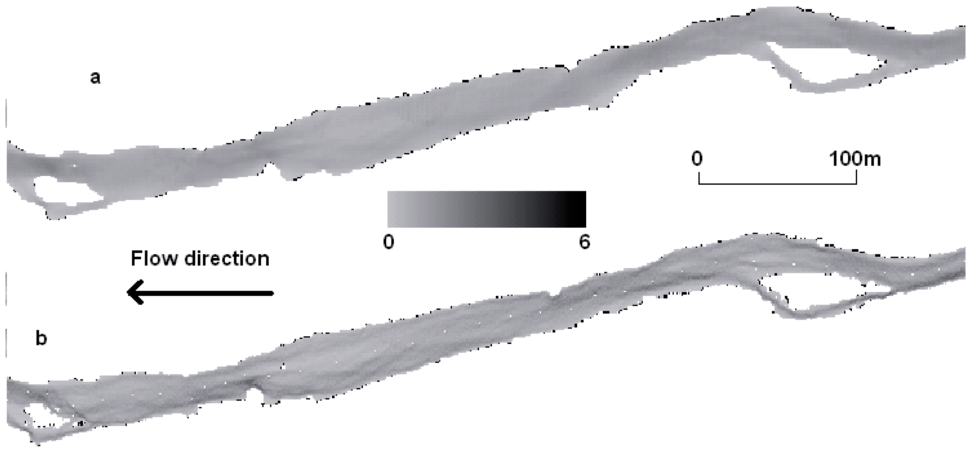


Figure 3. unit discharge generated for the sub reach of Walnut Gulch (Figure 1) using: (a) DELFT-3D flow (shallow water equations); (b) reduced complexity scheme. Total discharge $20m^3s^{-1}$.

CONCLUSIONS

Initial investigations into the applicability of a coupled 1D-2D model to simulate ephemeral channel flow, demonstrate: first, the ability of the 1D component to simulate downstream flow routing and channel transmission losses; second, that the coupled model is capable of reproducing distributed flow patterns that are broadly consistent with predictions from a more complex shallow water equation model. The simplicity and computational efficiency of the scheme presented affords the potential to investigate feedbacks between flow and channel evolution over historic timescales.

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