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DISCUSSION

Comment on ''Investigation of the hydrodynamics of flash floods in ephemeral channels: Scaling analysis and simulation using a shock-capturing flow model incorporating the effects of transmission losses'' by S.M. Mudd, 2006. Journal of Hydrology 324, 65–79

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Introduction

The paper of Mudd (2006) presents an investigation of flash flood propagation in ephemeral channels with porous beds, which experiences substantial infiltration. Studies on flash floods are of particular significance in the period when the concern over flash flooding is increasing over the world. For instance, the economic loss and the number of deaths due to flash flooding in China in recent years amount to over 50% of the total loss and deaths by flooding, therefore the government has recently launched a national program to cope with flash flooding disasters. In Europe, a number of major flash flood events have been documented (e.g., Gaume et al., 2004; Wallingford, 2005; Delrieu et al., 2005 to name a few), and the EU has recently approved research projects on flash flooding under the 6th Framework Program (e.g., HYDRATE, FLASH), which will develop a coherent set of technologies and tools aimed at the establishment of effective early warning systems.

Technically, the paper of Mudd (2006) focuses on the role of infiltration (i.e., transmission loss) in modifying flash flood propagation over porous beds. The one-dimensional St-Venant equations describing the channel flow are coupled with the Richards equation for the infiltration loss. Through scaling analysis and numerical solution of the governing equations, Mudd (2006) claims that the impacts of infiltration on flash flood propagation can be similar to those of friction. However, we find a major flaw in the governing equations, which appears to challenge part of the finding of Mudd (2006) connected with the flaw, as stated below.

St-Venant equations of open channel flows incorporating infiltration

The governing equations of fluid flows can be derived from the basic conservation laws in fluid dynamics (Batchelor, 1967; Roberson and Crowe, 1990; Liggett, 1994). For one-dimensional open channel flows, the St-Venant equations are based on the mass and momentum conservation laws, and can be found in, for instance, Cunge et al. (1980 reprinted version in 1994), Xie (1990) and Lai et al. (2002).

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When lateral inflow (or outflow) are considered, the St-Venant equations are

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=\tilde{q} \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right)+gA\frac{\partial h}{\partial x}=gA(S_0-S_\mathrm{f})+\tilde{q}u_\mathrm{q} \tag{2}$$

where t = time, x = streamwise coordinate, A = cross-section area, g = gravitational acceleration, h = flow depth, Q = discharge, $\tilde{q}$ = discharge of lateral inflow ($\tilde{q}>0$) or outflow ($\tilde{q}<0$) per unit length of the channel, S_0 = bed slope, S_f = friction slope, u_q = streamwise velocity component of the lateral inflow (outflow), and β = momentum correction coefficient (or, Boussinesq coefficient). Usually, $\beta \approx 1$ except for highly irregular cross-sections (e.g., compound channels with wide floodplains, see Cao et al., 2006a).

It is essential to note that Eqs. (1) and (2) are well applicable if lateral outflow (such as infiltration and evaporation), instead of inflow (e.g., tributary confluence and rainfall), is to be considered. This can be readily realized by simply taking the lateral flow discharge negative ($\tilde{q}<0$). Thus, the infiltration flux constitutes a sink term in the continuity of the channel flow, as Mudd (2006) states.

However, the contribution of the lateral inflow (or outflow) to the momentum conservation of the channel flow is dictated by not only the lateral flow discharge $\tilde{q}$, but also its velocity component u_q in the streamwise direction. Whilst the velocity of the lateral inflow (or outflow) and the angle it makes with the main channel flow velocity are for many cases difficult to estimate and may vary with the water stage (Cunge et al., 1980; reprinted version in 1994), for the case of outflow purely of infiltration through the channel boundary (and evaporation, if any, at the water surface of the channel flow), it is justified to set $u_\mathrm{q}\approx 0$ as the infiltration flow is nearly perpendicular to the channel flow. Therefore, the contribution of infiltration to momentum conservation is essentially negligible. This is in sharp contrast to the statement of Mudd (2006). The basis for the sink term quantifying the contribution of infiltration to momentum conservation [Eq. (9b)] in Mudd (2006) is unclear because no justification is provided.

Additionally, the resistance term, as quantified with the friction slope, is misprinted in the momentum conservation equation of the paper [Eq. (1b) or (9b)]. The resistance term, if put in the right-hand-side of the equation, should read $-gAS_\mathrm{f}$, instead of gAS_f.

Order-of-magnitude estimation

An order-of-magnitude estimation can be made to evaluate the quantitative effect of the unnecessary sink term, due to infiltration, in the momentum equation. For simplicity, we consider an idealized channel with rectangular cross-sections of constant width. The momentum Eq. (2) can be rewritten as

$$\frac{\partial (hu)}{\partial t}+\frac{\partial}{\partial x}\left(hu^2+\frac{1}{2}gh^2\right)=gh(S_0-S_\mathrm{f})-uf\alpha \tag{3}$$

where u = velocity of the channel flow, and f = infiltration rate. When the non-dimensional coefficient $\alpha = 1$, Eq. (3) corresponds to the momentum equation of Mudd (2006). But as we state above, the correct form of the momentum equation should assume $\alpha = 0$. To assess the contribution of infiltration to momentum conservation claimed by Mudd (2006) ($\alpha = 1$), as compared to that due to the combined contribution of channel bed and friction slope, we define a non-dimensional parameter Ri,

$$\mathrm{Ri}\equiv\left|\frac{uf\alpha}{gh(S_0-S_\mathrm{f})}\right| \tag{4}$$

For practical flash floods (mostly in mountain areas), we can make rough estimations: $u\sim O$ (10^0–10^1) (m/s), $h\sim O$ (10^0–10^1) (m), $abs(S_0-S_\mathrm{f})\sim O$ (10^{-3}–10^{-2}). If the infiltration rate $f\sim O$ (10^{-4}–10^{-3}) (m/s), as shown by Mudd (2006) (Fig. 2b), one has $\mathrm{Ri}\sim O$ (10^{-4}–10^0). Therefore, under certain conditions, incorporating a sink term due to infiltration in the momentum equation could considerably change the propagation of flash floods. Yet, it must not be forgotten that incorporating infiltration in the momentum equation is not justified, thus the Mudd (2006) model could produce incorrect results of flash flood propagation.

Numerical analysis

To illustrate how flash flood propagation can be influenced by the unnecessary infiltration term in the momentum equation, we carry out a numerical modeling test. The second-order TVD–WAF algorithm along with the HLL approximate Riemann solver (Toro, 2001) is used to numerically solve the governing equations, which can properly capture shock waves and deal with dry/wet bed problems. The modeling is essentially an application of the mathematical model of Cao et al. (2006b) to an adapted case without involving sediment transport, but incorporating infiltration.

It is noted that uncertainty in the estimation of the friction slope is inevitable, and the friction slope could considerably deviate from that calculated with Eqs. (6) and (13) of Mudd (2006). In the present analysis, let the channel width be large enough compared to flow depth so that the hydraulic radius is approximately equal to flow depth, i.e., $R\approx h$, the friction slope is approximated using the Manning roughness n by

$$S_\mathrm{f}=\frac{n^2u^2}{h^{4/3}} \tag{5}$$

The unit-width discharge ($q = uh$) hydrograph prescribed at the inlet of the channel is deduced from a specific case of Mudd (2006) with channel constant width $b = 2$ (m). For simplicity, we set $f = 0.0002$ (m/s), roughly the *smallest* value from Fig. 2b of the paper, without solving the Richard's equation, as our purpose here is just to demonstrate the qualitative behavior of Mudd (2006) model. Fig. 1 shows the unit-width discharge hydrographs at $x = 2$ km and 4 km, respectively, from the inlet of the channel. The hydrographs from Mudd (2006) model ($\alpha = 1$) is seen

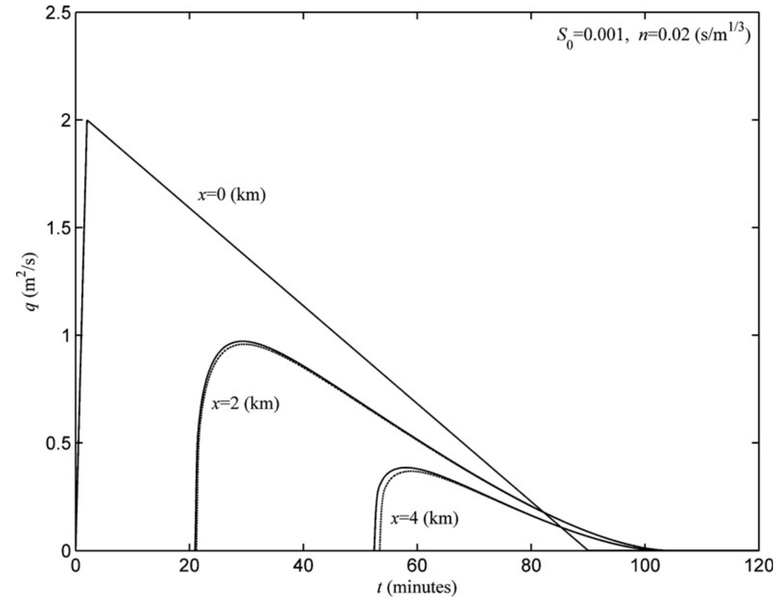

Figure 1 Computed unit-width discharge hydrographs at x = 2 km and 4 km, respectively, along with the specified hydrograph at the inlet of the channel (x = 0 km). Solid lines indicate the present model, and dash lines denote Mudd (2006) model.

to experience an appreciable lag in time, compared to the present model ($\alpha = 0$). This is quite understandable as the contribution of infiltration to the momentum conservation is represented as a sink term by Mudd (2006). The consequence in this respect could be risky in the sense of flash flood warning, as the flood wave at a specific site could have arrived sooner than predicted by Mudd (2006) model. When $S_0 = 0.01$ and/or $n = 0.04$ (s/m$^{1/3}$), the difference between the hydrographs from Mudd (2006) model and the present model seems less appreciable (not shown), as Ri defined in Eq. (4) becomes so small.

Conclusion

Mudd (2006) is complimented for the interesting work on flash flood propagation with infiltration loss. Mudd (2006) correctly incorporates the contribution of infiltration to the mass conservation of the main channel flow. However, the contribution of infiltration to the momentum conservation of the main channel flow is justifiably negligible on the physical basis. Unfortunately, Mudd (2006) incorporates a sink term of infiltration in the momentum equation without any justification. By order-of-magnitude estimation, it is shown that the sink term in the momentum equation claimed by Mudd (2006) can be as large as the combined term of gravity and resistance (expressed with bed slope and friction slope), which can erroneously affect the propagation of flash floods. Especially, flood waves could have arrived sooner than predicted by Mudd (2006) model under certain cases, which is significant for flood warning. It is concluded that the finding of Mudd (2006) on the role of infiltration in modifying flash flood propagation needs to be reformulated.

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