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method has the inherent property of exhibiting the physical diffusion as demonstrated by the extended KM method.

Appendix. References

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Discussion by David A. Woolhiser,[4] Member, ASCE

The writer, like the author, also hopes that his paper will "focus the attention of researchers and practitioners so that the controversy may be brought to a timely end." However, the idea that there is a controversy is, in itself, somewhat controversial. The paper cited by the author in the introductory section (Hromadka and DeVries 1988) deals with a demonstration of "errors" due to kinematic routing (1) By a program containing a mistake; and (2) for a case in which currently accepted criteria (developed by the author) would indicate that kinematic routing is not appropriate. The discussions to that cited paper point out these factors (Goldman 1990; Unkrich and Woolhiser, 1990; Woolhiser and Goodrich 1990).

Later the author states, "The presence of numerical diffusion and dispersion in a numerical solution using the finite difference method is at the crux of the controversy surrounding the kinematic wave model." Thus it appears that the author's controversy is about numerical methods rather than the kinematic wave model itself. It is clear from the literature that some ill-advised finite difference schemes have been used, and it is well known that the errors of approximation of such schemes can be appreciable and are grid dependent. However, it is not appropriate to conclude that "typical" finite difference solutions feature appreciable amounts of numerical diffusion and dispersion. It is clear that the Muskingum-Cunge method has some very desirable properties, but it is also not immune to numerical error if the time and space steps are poorly chosen.

Some other points deserve discussion. They are described under the author's headings.

Background

It is incorrect to state that kinematic modeling of unsteady open-channel flow implies that such flows can be visualized as a succession of steady uniform flows. While it is true that there is a region of uniform, unsteady flow during the rising stage for flow on a plane or in a channel with uniform

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later inflow (which also occurs for the St. Venant equations within the zone of determinacy of the initial condition), in the general case the water-surface slope will vary with space and time. In this regard, the reference to simplification of the equation of motion to a statement of uniform flow may result in some confusion. The writer prefers the approach of Lighthill and Whitham (1955), who state that kinematic waves exist when there is a functional relationship between flow and concentration (quality per unit distance). For hydraulic problems where the channels are well defined, this relationship reduces to a Chezy or Manning formula; for hydrologic applications it is better interpreted as a statistical relationship between the discharge and the mean storage per unit area averaged over some representative area.

Kinematic Wave Solutions

Analytic solutions can be obtained for the nonlinear form of (2) and are useful in examining numerical errors of finite difference schemes. Shock development in overland flow applications usually does not occur as a result of wave steepening but rather is a consequence of the geometric representation. For example, no shock would occur in kinematic modeling of runoff from a concave upward hill slope if the slope is represented as a smooth curve. However, shocks would occur if the slope is represented as a cascade of planes.

Kinematic Shock

The author's use of the term *kinematic shock* to represent several different physical phenomena may lead to some confusion. Such phenomena historically have been called surges (Keulegan 1949). There is no valid reason to change the terminology because there is no perfect correspondence between surges and kinematic shocks. For example, in overland flow applications whenever there is an abrupt increase in hydraulic resistance or a decrease in the slope or lateral inflow, kinematic shocks will inevitably be generated mathematically as a result of the properties of the kinematic wave equation. The fact that these shocks are damped out in finite difference solutions is irrelevant because they occupy such a limited portion of the solution domain. Under the same real-world circumstances, surges with an abrupt front may or may not be generated depending on the magnitude of the diffusionlike effects. On the other hand, intermittent surges or roll waves will form on steep slopes and, indeed, the St. Venant equations become unstable at high Froude numbers, as the author states. However, the kinematic wave equations do not exhibit such instabilities, and may do a good job in describing the bulk hydrologic behavior of the system. Obviously the solutions of the kinematic wave equations would show no evidence of the roll waves and only the statistical interpretation of the discharge-storage relationship would be appropriate.

Summary and Conclusions

The fourth and fifth paragraphs in this section present a reasoned discussion of applicability of kinematic and diffusion wave approaches. The writer feels that the issue of choice between the kinematic wave and unit hydrograph methods for practical runoff computations can only be resolved by objective testing of alternative models using excellent hydrologic data from experimental watersheds.

Appendix. Reference

Keulegan, G. H. (1949). "Wave motion." *Engineering hydraulics*, H. Rouse, ed., John Wiley & Sons, Inc., New York, N.Y., 745–756.

Closure by Victor M. Ponce,[5] Member, ASCE

The writer wishes to thank Goodrich, Perumal, and Woolhiser for their interest in the paper, Goodrich's concern regarding the role of Manning's *n* as a calibration parameter in kinematic watershed models touches the very heart of the controversy about kinematic wave models. The writer was cautioning against the practice of varying Manning's *n* to match calculated results and observed data, when the diffusion of the calculated results is due solely to a numerical condition and not to an intrinsic physical condition. In this case, the calculated results will be grid dependent throughout a range of grid sizes, and different grid choices will require different values of Manning's *n*. However, only one value of Manning's *n* can be the correct one from the physical standpoint. If the correct value of Manning's *n* were known a priori, one could conceivably adjust the grid choice to match, but this proves to be too cumbersome a procedure. More often, it is the choice of grid that is set a priori, and the Manning's *n* adjusted accordingly. It is this type of "calibration" that the writer was cautioning against in the paper. Goodrich is correct in pointing out that in practice, topographic irregularities have the effect of adding diffusion. It is impossible to separate the latter from either the numerical diffusion already present in the model or from the physical diffusion (if any) which the model hopes to simulate. This added complexity gives the model not so much a statistical flavor, as Goodrich has argued, but rather, a conceptual dimension, as the writer had originally stated.

In setting areal limits for the applicability of the kinematic wave method, the writer qualified his 1-sq-mi (2.59-km^2) limit by stating that it was somewhat arbitrary. Goodrich's successful application of the method to a 2.5-sq-mi (6.47-km^2) watershed only proves that this, and other such limits—within reason—may be exceeded in certain cases, provided enough care is exercised in the modeling. For general practice, however, it seems prudent to restrict the routine usage of the method to small watersheds, the smaller the better. Goodrich may be correct in pointing out that "the errors associated with areal rainfall and excess runoff estimation are significantly greater." However, in the context of this paper, it only serves to cloud the issue. The writer believes that distributed deterministic modeling will eventually carve its niche not by lumping these effects together, but by accounting for them separately in the most rational way possible.

Perumal has called attention to the extended Kalinin-Milyukov (KM) method as presented by Apollov et al. (1964) and contrasted it with the Muskingum-Cunge (MC) method. The KM and MC methods are indeed very similar, as Perumal asserts, since they are both derived from the kinematic wave equation (Miller and Cunge 1975). The difference is that

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