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COMPUTER SIMULATION OF FLOWS IN A CHANNEL WITH EXTREMELY IRREGULAR BED TOPOGRAPHY

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ABSTRACT

Practical comparison of the modeling systems for surface waters HEC-RAS and MIKE 21 is provided, using the ephemeral Whitewater River, California as an example. The models are based on different schematization of physical flows and are widely used throughout the world for flood inundation assessment. The study reach of the river is characterized by extremely irregular bed topography which can have a significant effect on flood flow hydraulics. The models were developed from available topographic and hydrological data and were used to simulate flood flow through the study reach. The results of comparative simulations demonstrate the efficiency and limitations of the models for simulating complex spatial flows in highly irregular channels and illustrate inaccuracies that can arise from these models in similar applications.

Keywords: computer simulation, flood, ephemeral river, irregular channel

1. INTRODUCTION

Prediction of flood flow dynamics and water levels in channels with extremely irregular bed topography presents a significant challenge to river engineers. Typical environments characterized by complex ground surfaces and non-uniform flood flow pattern include ephemeral streams, alluvial fans, braided rivers, complex urban areas and floodplains, etc. Flooding of such environments presents unique problems in terms of quantifying flood levels and extent of inundation and devising reliable mitigation strategies.

A variety of research and commercial computer models is currently available for simulation of open-channel flows. Due to the relative simplicity and ease of use, one-dimensional (1-d) models are often employed in flood assessment studies including complex riverine environments. However, adequate simulation of complex spatial flows may require application of more sophisticated (2-d or 3-d) models which are more difficult to master and which require more input data. The information regarding practical applicability, limitations, and inaccuracies of different modeling approaches in various riverine environments is insufficient. A considerable degree of experience and judgment may be required to select the model most appropriate for the particular circumstances, especially when information on stream flow conditions and hydraulics is not available a priori (which is often the case, for example, in arid environments). Often modeling tools are selected for projects based on institutional inertia, budget restrictions, political reasons, or due to insufficient understanding model ability to simulate the key physical processes.

This paper is focused on comparing two different approaches to modeling open channel hydraulics in irregular channels, using the ephemeral Whitewater River near Palm Springs, California as an example. Due to the lack of direct flow measurements, the models were not rigorously calibrated or validated. The intention of the paper is to highlight the relative differences in the results obtained by different modeling approaches based on different schematization of the simulated phenomenon. The results presented demonstrate the efficiency of the models used for simulating flows in complex channels and illustrate inaccuracies that can arise from these models in similar applications.

2. SITE DESCRIPTION

The Whitewater River is the main drainage of the Coachella Valley in South California. The watershed area of the river is approximately 3100 km^2. The Whitewater River originates in the San Bernardino Mountains and flows southeast into the Salton Sea. The total length of the river is about 110 km. Due to the arid environment, runoff events are infrequent and typically produced by individual storms of high intensity. Long periods of several years or more may pass between significant flood events. The river channel is dry most of the time and is used for recreational purposes, typically golf courses.

The study reach includes the portion of the river channel near Palm Springs containing the Cimarron Golf Course (Figure 1). The golf course reach extends approximately 2600 m upstream from the Ramon Road Bridge. The channel width is 360-460 m. The overall slope of the channel bed is nearly 0.01. The channel is bordered by concrete faced levees providing flood protection for the adjacent urbanized areas. The ground within the golf course reach is extremely irregular (Figure 2), with numerous 1-3 m high ground undulations and similarly sized depressions. From a morphological perspective, the golf course reach represents a braided network of narrow, winding, deep sand-bed “sub-channels”, separated by large, stabilized grass-covered “islands”, with up to a 6-8 m range of ground elevations between the topographic features. This uneven topographic relief creates numerous local hydraulic controls and hydraulically disconnected areas, which significantly complicates the hydrodynamic analyses. During infrequent runoff events, flow in the study reach is highly turbulent (Figure 3). Due to the extremely rare occurrence of significant flood events in the river, no information on high flow hydraulics is available for the golf course reach.

3. MODELING APPROACH

The objective of this study was to quantify the flood flow hydraulics and water surface profiles in the golf course reach of the Whitewater River using two different computer hydraulic models based on different numerical schematizations of the open-channel flow. These models are the U.S. Army Corps of Engineers (USACE) 1-d model HEC-RAS and the Danish Hydraulic Institute (DHI) 2-d model MIKE 21. The HEC-RAS model is extensively used throughout the world for modeling the hydraulics of open channel flow (e.g. Kresch et al., 2002; Mastin and Olsen, 2002). A 1-d model, however, is generally applicable to channels with sufficiently simple geometry and uniform transverse distribution of flow velocities and water surface elevations. The 2-d MIKE 21 model provides a well-tested tool for quantifying complex spatial flow hydraulics (e.g. McCowan and Collins, 1999; Juza and Barad, 2000; Eskilsson et al., 2002). The 1-d and 2-d hydraulic models were developed using available topographic and hydrological data and run for fixed bed conditions. This paper compares predictions obtained from these two models for the 100-year peak flow (estimated at 1330

m^3/s). The following sections describe the development of the two models, derivation of input data used in the models, key assumptions, and results obtained from the numerical simulations.

Figure 1 Study reach of Whitewater River containing Cimarron Golf Course within dry channel. Area shown is approximately 3500 by 1900 m. Flow direction from top left to bottom right. Photograph provided by Coachella Valley Water District, California.

Figure 2 Cimarron Golf Course in Whitewater River channel during dry season**.**
Photograph of 29 April 2003 by L. Joseph Howard (Northwest Hydraulic Consultants).

Figure 3 Cimarron Golf Course on 11 January 2005 during flood flow of about 250 m^3/s**.**
Photograph courtesy of Mekbib Degada (Riverside County, California).

4. 1-D HYDRAULIC MODELING

4.1 Description of Computer Model HEC-RAS

HEC-RAS (USACE, 2004) is a computer program designed to perform 1-d, steady and unsteady flow, water surface profile computations. In steady state mode, the program is intended for computing both sub-critical and super-critical flows. The basic computational procedure is based on the solution of the 1-d energy equations for gradually varied flows. The momentum equation is utilized in situations where the water surface profile is rapidly varied. The unsteady flow component is based on the solution of the equations of conservation of mass and momentum, and was developed primarily for sub-critical flow regime computations. The basic required inputs to the model are channel geometry, encroachments and ineffective flow areas, channel roughness, contraction and expansion losses due to changes in cross sections, flow regime, initial and boundary hydraulic conditions.

The HEC-RAS model is based on the following assumptions: the channel is sufficiently straight and uniform so that the flow may be physically represented by a 1-d flow model; the flow is in streamwise direction and normal to the cross section; the water surface elevation and velocity vary only in the longitudinal direction; the water surface is horizontal in each cross section; the velocity is uniformly distributed over the cross section; transverse effects are not explicitly considered; the pressure distribution is hydrostatic; and the river channel slope is small (less than 0.1).

4.2 HEC-RAS Model Development

The model contained a 2300 m long leveed reach of the Whitewater River upstream of the Ramon Road Bridge. Cross section data for the model were obtained from a digital 0.6 m contour as-built grading plan. Altogether, 51 cross sections spaced from 15 to 106 m were specified at locations of key topographic relief in the modeled reach. Shorter intervals between cross sections were used at locations with abrupt changes in the bed relief in an attempt to better resolve flow hydraulics. The lowermost cross section coincided with the Ramon Road Bridge. In the absence of any information on hydraulic conditions in the golf course reach, ineffective flow areas were not specified on the model cross sections. Contraction and expansion coefficients (0.1 and 0.3, respectively) were specified in accordance with the USACE (2004) recommendations. Manning's roughness coefficient of the channel was assumed to be 0.03, which is a typical roughness value for "earth, winding channel with grass" in accordance with Chow (1959). A constant water inflow of 1330 m^3/s was specified at the uppermost cross section as upstream boundary conditions. A controlling water stage was determined from the normal-depth calculations and specified as downstream boundary condition. The HEC-RAS model was run in steady state mode with mixed flow regime, computing the water surface profile for both sub-critical and super-critical flow regimes.

4.3 HEC-RAS Model Results

Longitudinal water surface profile, stream velocities, and Froude numbers computed using the HEC-RAS model for the 100-year flow are shown in Figure 4. The channel stationing is measured along the channel centerline upstream of the Ramon Road Bridge. Apparent step-like pattern in the water surface profile is caused by local reduction of channel conveyance and associated backwater effects due to topographic undulations. Local dips in the water surface profiles are associated with super-critical flow reaches. Computed flow velocities range from about 1.4 to 6.2 m/s, with the reach-average value of 3.0 m/s. Lower local velocities are associated with the areas characterized by reduced water surface slopes. Higher flow velocities are computed for reaches with steeper water surface slopes. According to the model results, Froude numbers in the study reach range from about 0.3 to 1.8. Local energy slopes range from 0.0005 to 0.026, with lower slopes corresponding to the reaches with reduced channel conveyance and greater flow depths. The reach-average energy slope is about 0.006.

It is seen from the HEC-RAS model results that stream flow in the study reach is extremely non-uniform and is greatly influenced by the complex channel geometry. It appears that at many locations, particularly downstream of significant topographic undulations, the flow regime is super-critical (Froude number is greater than one). It should be remembered, however, that the results obtained from the HEC-RAS model are section-averaged and do not reflect any transverse variations in flow hydraulics.

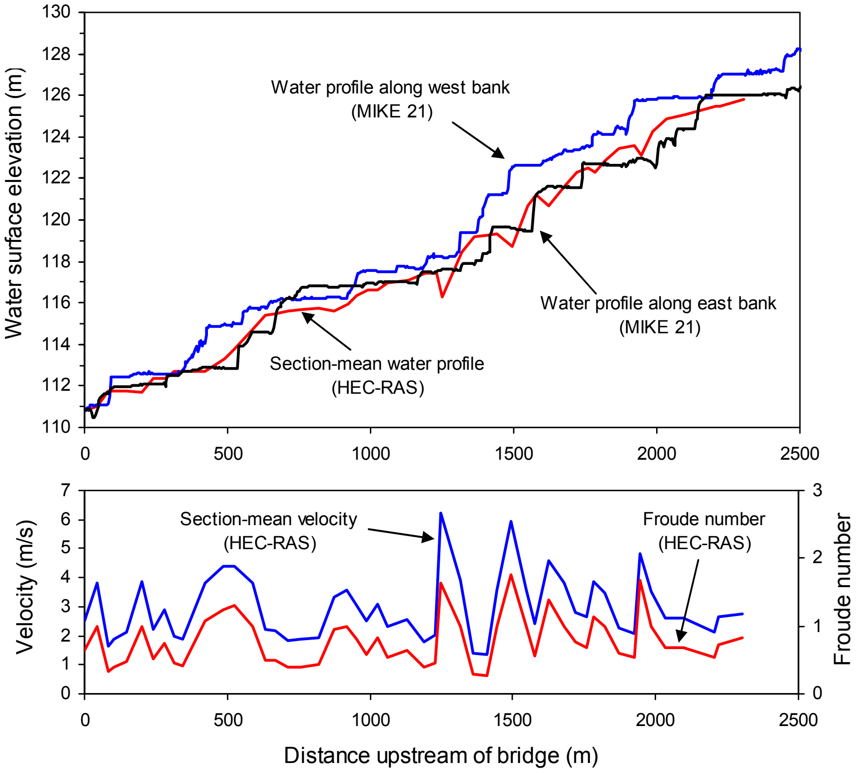

Figure 4 Longitudinal water surface profiles, stream velocities, and Froude numbers computed for 100-year flow.

5. 2-D HYDRAULIC MODELING

5.1 Description of Computer Model MIKE 21

MIKE 21 (DHI, 2003) is a 2-d implicit finite difference scheme model used for computation of unsteady open channel flows. The computational procedure is based on the solution of the depth-averaged fully time-dependent non-linear equations of conservation of mass and momentum. The water levels and flows are resolved on a rectangular grid covering the area of interest. The main input parameters for the MIKE 21 model are channel surface topography, initial water surface elevation, bed resistance, flooding and drying tolerances (turning computational grid cells on and off), flow turbulence characteristic, and hydrographic boundary conditions. The output parameters of a simulation include water depth and 2-d water flux components at each grid point in the computational domain for each time step. All output data can be post-processed, analyzed, and presented in various graphical formats.

5.2 MIKE 21 Model Development

A rectangular grid of the golf course reach of the Whitewater River was developed using the digital as-built topographic mapping. The model grid cell size was set to 2 by 2 m. This grid scale is sufficiently dense to describe the relatively small-scale topographic variability of the golf course, as well as the transverse flow patterns between topographic features within the channel. The model contained a 2700 m long reach upstream of the Ramon Road Bridge. The computational domain was bordered by the two levees with open upstream and downstream boundaries. To eliminate the effect of the flow boundary conditions on the model solution at the upper and lower limits of the golf course, the modeled reach was extended upstream by 100 m and downstream by 40 m. The added entrance and exit sections of the channel were transitioned to a rectangular shape at the model boundaries to provide smooth water inflow and outflow conditions. The channel roughness coefficient of 0.03 was the same as that used in the HEC-RAS model. Flooding and drying tolerances (0.02 and 0.01 m, respectively), as well as eddy viscosity (0.4 m^2/s) were developed using procedures recommended by DHI. A constant water inflow of 1330 m^3/s was employed as upstream boundary condition. Initial water surface was assumed horizontal. Simulations started with gradually lowering the downstream stage to the normal depth value, and the model was then run until a steady flow condition was obtained. The simulation time step was set to 0.2 s to maintain computational stability (Courant numbers less than 1) for velocities up to 10 m/s.

5.3 MIKE 21 Model Results

Longitudinal water profiles along the west and east banks of the golf course reach computed using the MIKE 21 model for the 100-year flow are shown in Figure 4. Selected cross section water surface profiles are shown in Figure 5. Stream velocities are shown in Figure 6.

The modeling results indicate that flood flow through the golf course reach has a complex, highly non-uniform and spatially variable pattern. Stream flow is split into a few distinct paths coinciding with deep, narrow sub-channels that convey floodwaters through the golf course. The flow paths are winding between high grounds and in many areas the sub-channels have poor hydraulic interconnections. Numerous localized dry areas represent summits of the high ground undulations. Water depths in the study reach range from a few centimeters to over 7 m. Flow velocities range from near-to-zero up to 7-8 m/s and have extremely non-uniform distribution over the golf course area. Lower velocities are computed for ponded areas associated with high ground undulations located in various parts of the channel. Higher velocities are computed along the deep, narrow sub-channels, as well as in the areas where flow spills over elevated topographic features representing local hydraulic controls. Flow regime in the study reach is both sub-critical and super-critical. Sub-critical flow conditions are mostly associated with ponded, low gradient and low velocity areas, while super-critical flow is computed for steep gradient, high velocity reaches.

The extremely irregular channel topography, poor hydraulic interconnections, and non-uniform spatial flows between different parts of the golf course area result in a complex, step-like water surface pattern, with spatially alternating ponded and steep gradient reaches. Numerous topographic features control water levels within the ponded areas and result in abrupt lateral and longitudinal drops in water surface elevations. The computed water surface data reveal significant local variations in water levels resulting in up to 2-3 m difference in water surface elevations at opposite banks of the study reach. This has implications for prediction of flood hazards in irregular channels.

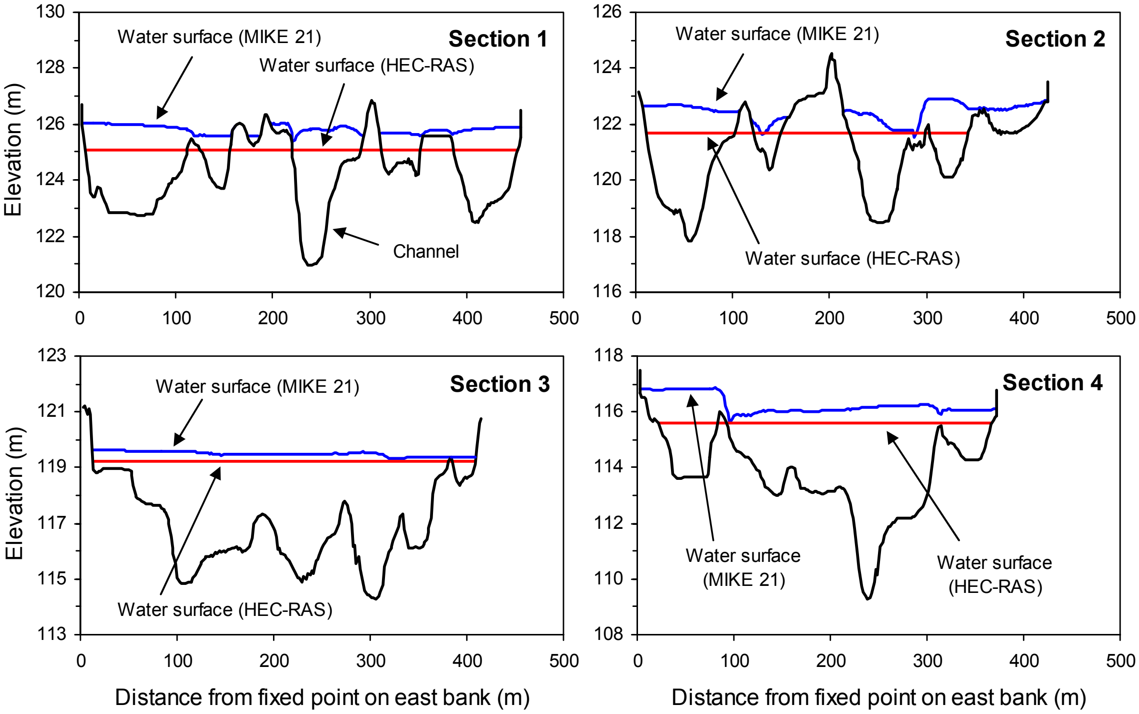

Figure 5 Comparison of cross section water surface profiles from MIKE 21 and HEC-RAS models. Location of cross sections is shown in Figure 6.

6. COMPARISON OF RESULTS

Comparisons of the longitudinal and cross section water surface profiles computed by the 1-d HEC-RAS and 2-d MIKE 21 models are shown in Figures 4 and 5. It is seen that the HEC-RAS model tends to underestimate water surface elevations. In areas with relatively simple cross section geometry (e.g. cross section 3 in Figure 5) both the 1-d and 2-d models show similar results, with the difference in the predicted water levels less than 0.5 m. However, in reaches with complex bed topography (e.g. sections 1, 2, and 4 in Figure 5) the HEC-RAS model predicts local water surface elevations up to 2 m lower than those computed by the MIKE-21 model. The longitudinal water surface profile predicted by the HEC-RAS model underestimates by 1-2 m water stages computed by the MIKE 21 model along the west bank (Figure 4). Both the models predict quite similar water surface elevations along the east bank of the golf course. The differences in water surface data between the models result from the inability of the 1-d modeling approach to simulate transverse flows, complex interconnected flow paths, and localized backwater ponding from topographic features. The difference in the predicted water elevations revealed in this study is unacceptable for quantifying flood hazards and inundation levels in rivers. Therefore, 1-d models are inadequate and should not be used for flood assessment of streams with highly irregular channels.

The lack of the measured data did not allow the calibration of the models developed. Sensitivity runs with roughness coefficients ranging from 0.02 to 0.05 indicated quite significant (up to nearly 0.5 m) changes in the computed water levels caused by varying the channel roughness. However, relative difference between the results produced by the two models for different channel roughness remained practically unchanged.

It should be remembered that the results from the computer simulations were obtained for fixed bed conditions. In reality, high stream velocities during the simulated flow would likely result in scour and deposition within the golf course reach, which would alter channel topography and affect local flow conditions. However, analysis of potential morphological adjustments within the study channel is beyond the scope of this paper.

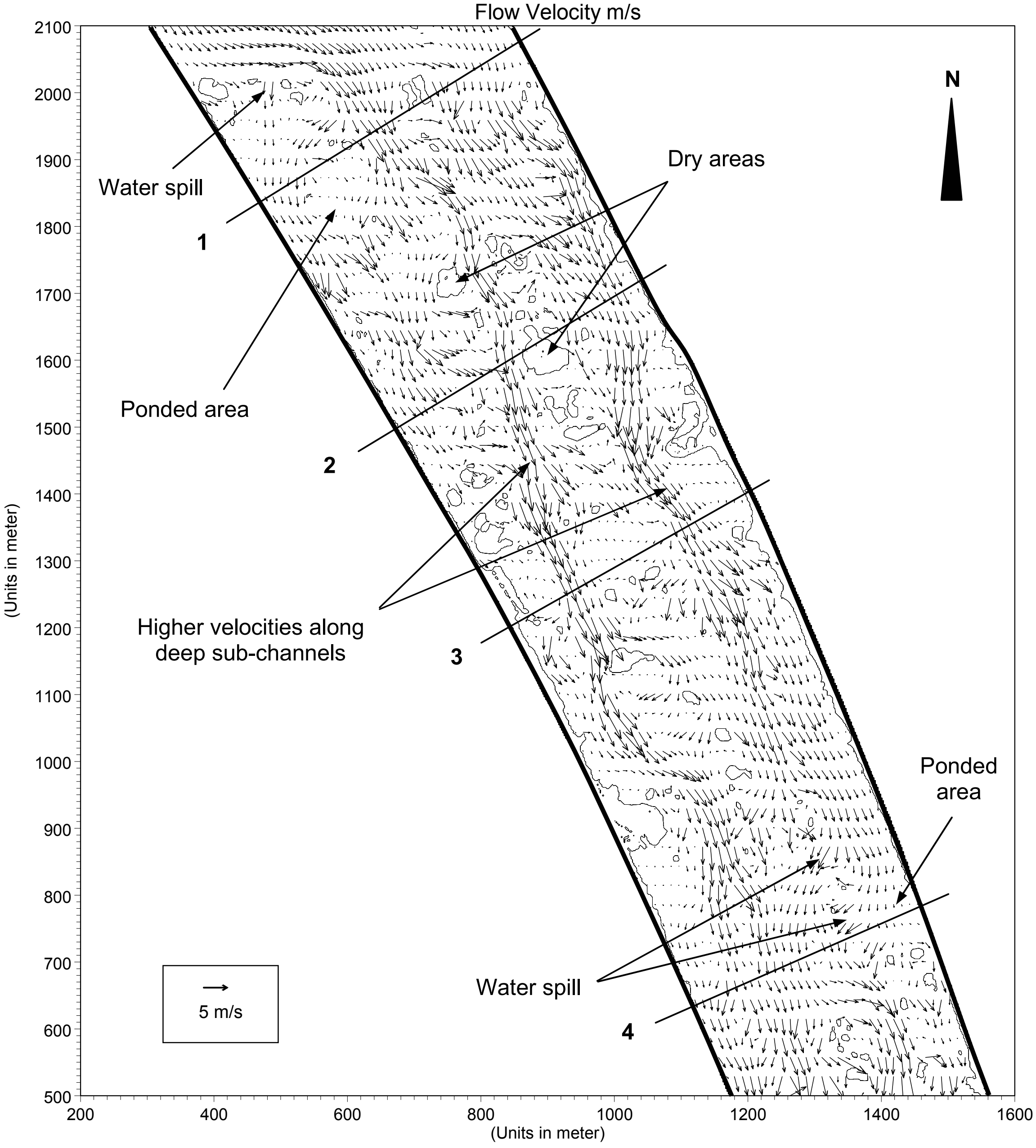

Figure 6 MIKE 21 model results: Stream velocity for 100-year flow.
Cross sections shown were used in comparison of MIKE 21 and HEC-RAS results.

7. CONCLUSIONS

The applicability of two different computer models (1-d HEC-RAS and 2-d MIKE 21) to simulation of complex physical flows in highly irregular channels was tested, using a golf course reach of the Whitewater River near Palm Springs, California as an example. The two models are based on different schematization of the simulated phenomenon and are often used in flood assessment studies. The results of comparative simulations indicate that the 1-d modeling approach can not adequately characterize complex spatial flow conditions and does not provide sufficiently accurate representation of water surface elevations in channels with extremely irregular bed topography. Significant underestimation of flood inundation levels may result from the use of 1-d models in complex topography environments. Quantification of spatial flow hydraulics characterized by mixed sub-critical and super-critical flow regimes and significant transverse effects require application of the more sophisticated 2-d modeling approach. Although the models used were not rigorously calibrated or validated, the results of this study clearly illustrate possible inaccuracies in the predictions that may arise from using oversimplified 1-d approach to modeling flow phenomena in similar applications.

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