PART SEVEN

MODELING, COMPUTER APPLICATIONS, AND GEOGRAPHIC INFORMATION SYSTEMS

BEYOND STEADY STATE: FEMA PERSPECTIVE COMPUTER PROGRAMS—THEIR USE IN SUPPORTING NFIP MAPS

Alan A. Johnson
Federal Emergency Management Agency

Thomas W. Smith
Michael Baker Jr., Inc.

Introduction

To join the National Flood Insurance Program (NFIP), a community must adopt and enforce the minimum floodplain management regulations required for participation. The Federal Emergency Management Agency (FEMA) works closely with state and local community officials to identify flood hazard areas and flood risks. The floodplain management requirements within the flood hazard areas are designed to prevent new development from increasing the flood hazard and to protect new and existing buildings from anticipated flood events. Communities must ensure that their adopted floodplain management regulations and enforcement procedures meet NFIP requirements, and must update the regulations when additional data are provided by FEMA or when federal/state standards are revised.

In support of the NFIP, FEMA has identified flood hazards and mapped them on Flood Insurance Rate Maps (FIRMs) and, in some cases, Flood Boundary and Floodway Maps. Several areas of flood hazard are commonly identified on the FIRMs, based on detailed hydrologic and hydraulic analyses. One of these areas is the Special Flood Hazard Area (SFHA), defined as an area of land that would be inundated by a flood having a 1% chance of occurrence in any given year, a flood also referred to as the base, or 100-year, flood. Development may take place within the SFHA, provided that it complies with local floodplain ordinances that meet the minimum federal requirements.

Many SFHAs were determined from detailed hydrologic and hydraulic analyses performed by reputable engineering firms or federal agencies that contracted with FEMA to perform these analyses and to prepare flood maps and reports for the community. From the analyses and maps, FEMA prepares and distributes Flood Insurance Study (FIS) reports and FIRMs that present the limits of the SFHAs, base flood elevations (BFEs), and flood insurance risk zones.

To change the flood hazard information presented in the FIS report and on the FIRM, NFIP regulations require that scientific or technical data be provided to demonstrate that the change is warranted. If physical changes that would change the BFEs have occurred along a stream or flooding source, several procedures are in place to effect a revision to the report and map. One procedure involves revising a specific FIRM panel based on technical data submitted by the community or an individual appellant. If changes to the floodplain have occurred since the FIS was completed, it is the community's responsibility to furnish the data reflecting the nature and effects of the changes. Once these data are provided, a map revision can be accomplished by physically changing the FIRM or issuing a Letter of Map Revision. Community officials and others who wish to request revisions to NFIP maps may find it necessary to obtain the supporting hydrologic and hydraulic data used to establish the SFHA. These supporting data usually include the results of analyses performed using computer programs. To ensure that these programs are available to all parties impacted by the flood insurance/floodplain mapping developed or revised through the NFIP, specific requirements for the availability and use of computer programs have been established and are contained in the NFIP regulations.

Computer Programs Acceptable for NFIP Use

Numerous computer programs (models) have been used to support the determinations and designations of SFHAs on NFIP maps. The most frequently used hydraulic computer program for determining water-surface elevations in riverine situations is HEC-2, developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center. The WSPRO model, developed by the U.S. Geologic Survey/Federal Highway Administration (FHWA), and the WSP2 model, developed by the U.S. Soil Conservation Service, are other examples of widely used one-dimensional steady-flow models developed and supported by federal agencies.

However, in many instances, complex flow conditions may dictate that one-dimensional steady-flow models alone are not sufficient to determine the water-surface elevations in these situations. One-dimensional unsteady-flow and two-dimensional steady- and unsteady-flow models are being used to analyze these more complex conditions. Many of these complex conditions can be found in natural river systems, but many more have been caused by the construction of human-made structures in the floodplains (e.g., roads, levees, bridges, culverts, buildings).

DAMBRK and DWOPER, developed by the National Weather Service, are examples of one-dimensional unsteady-flow models accepted by FEMA for NFIP use. FESWMS-2DH, developed by FHWA, is a finite-element surface-water modeling system used to simulate steady and unsteady two-dimensional flow in the horizontal plane, and has been used to determine water-surface elevations in support of the NFIP. Specific regulations relating to the acceptance of these and other computer programs for NFIP use are discussed below.

NFIP Regulations Relating to Computer Programs

Computer programs used to perform hydrologic or hydraulic analyses in support of an NFIP map revision must meet all of the requirements of Paragraph 65.6(a)(6) of the NFIP regulations. The purpose of these requirements is to ensure that all parties requesting revisions have access to the supporting data used to establish the SFHA on an NFIP map. These programs must meet several criteria:

- The program must have been reviewed and accepted by a governmental agency responsible for implementing programs for flood control and/or the regulation of floodplain lands. For computer programs adopted by non-federal agencies, additional certifications by a responsible agency official are required for review, testing, and acceptance.

- The program must be well documented, including source codes and user's manuals.

- The program must be available to FEMA and all present and future parties impacted by flood insurance/floodplain mapping developed or revised through the use of the program. For computer programs not generally available through federal agencies, the source code and user's manuals must be sent to FEMA free of charge with fully documented permission from the owner that FEMA may release the code and user's manuals to such impacted parties.

For the purposes of certification by non-federal agencies, computer programs adopted by regional flood control districts involved in designing flood control structures or in regulating floodplain lands are accepted only if all other requirements of Paragraph 65.6(a)(6) of the NFIP regulations can be met. Even if a computer program (model) meets the NFIP review and acceptance criteria, the correct application of the model to the particular flow conditions is the user's responsibility and review of its acceptability in support of a revision request will be determined under Part 65 of the NFIP regulations.

Examples of Applications of These Models

Discussed below are some typical examples where more complex flow situations have been analyzed through one- and two-dimensional steady- and unsteady-flow models.

Example 1—Large Tributary Inflows to Main Stem

In this example, river flows are controlled by upstream dams and reservoirs. For this reason, tributary inflows have a significant effect on the resulting 100-year water-surface elevation in the main stem of the river. During significant flooding, flows from the tributary will cause unsteady flow in the river's main stem.

The DWOPER model was used to determine the effects of tributary inflows on the main stem of a controlled river. In this case, the tributary inflows were combined with the main stem base flow and then routed to determine the flows above and below the confluence point. The resulting flows were used in the steady-state backwater program to calculate the water-surface elevations. The main stem water-surface profile was compared to the tributary-influenced profile to determine the controlling water-surface profile for NFIP purposes.

Example 2—Effects of Levees on Peak Flows

In this example, a major levee is located on the stream. When overtopped, the levee will allow off-stream storage behind it. Flood peaks will be affected by these levee overflows and off-stream storage. Encroachments in the off-stream storage areas were evaluated to ensure that flood peaks downstream would not be increased by future development (fill) in these areas due to loss of storage.

The DWOPER model was used to simulate the progression of the 100-year flood wave through the reach of stream affected by the levee. The DWOPER model was used because it can simulate flow over and storage behind levees. These resulting peaks were used in the steady-state backwater program to calculate water-surface elevations and floodways.

Example 3—Bridge, Many Islands, and Bifurcations

In this example, a river reach that is hydraulically complex, with a bridge, many islands, and bifurcations present during 100-year flood conditions, is to be modeled. Because of the hydraulic complexity, the FESWMS-2DH model was used. For purposes of developing a floodway, the FESWMS-2DH model results were used to calibrate the 100-year water-surface elevations determined in the one-dimensional HEC-2 model. The HEC-2 model was then used to establish an equal-conveyance floodway.

A STOCHASTIC INTEGRAL EQUATION ANALOG FOR RAINFALL-RUNOFF MODELING

T. V. Hromadka II
Boyle Engineering

Abstract

The complexity of rainfall-runoff modeling and the apparent lack of success in significantly improving the accuracy of such modeling are well documented. In this paper, a multi-linear unit hydrograph approach is used to develop subarea runoff, and is coupled with a multi-linear channel flow routing method. The spatial and temporal rainfall distribution over the catchment is equated to a known rainfall data source. The resulting model structure is a series of stochastic integral equations, one equation for each subarea. A cumulative stochastic integral equation is developed that includes the spatial and temporal variabilities of rainfall. The resulting stochastic integral equation is an extension of the well-known single-area unit hydrograph method, except that the model prediction of a runoff hydrograph is a distribution of outcomes (or realizations).

Introduction

The complexity of rainfall-runoff modeling and the apparent lack of success in improving its accuracy are well documented (for example, Jakeman and Hornberger, 1993; Loague and Freeze, 1985; Hornberger et al., 1985; Hooper et al., 1988; Beven, 1989; Hromadka and Whitley, 1989). An apparent barrier to improvement in modeling accuracy is the lack of accurate rainfall data. Raines and Valdes (1993) state that "the estimate of the rainfall parameters is the most subjective task and seems to be responsible for the major sources of error." In this paper, unit hydrographs are used to estimate subarea runoff, which is then coupled to a multi-linear channel flow routing analog to develop a link-node model network. Jakeman and Hornberger (1993) observed a "predominant linearity in the response of watershed over a large range of catchment scales even if only a simple adjustment is made for antecedent rainfall conditions. The linearity assumption of unit hydrograph theory therefore seems applicable in temperate catchments and works just as well for slow flow as for quick flow."

Stochastic Rainfall-Runoff Model Development

The catchment is divided into hydrologic subareas, R_j, such as discussed in Hromadka et al. (1987). Each R_j is homogeneous in that a single loss function transform, $F_j(\bullet)$, applies in the subarea. The effective rainfall (or rainfall less losses) is given by $e_j^i(\bullet)$, for storm event i, where

$$e_j^i(t) = \int_{R_j}\int F_j(P^i(x,y,t))\ dxdy\ /\ A_j \tag{1}$$

where A_j is the area of R_j. The point rainfall is written as a sum of proportions of the available rain gauge data by

$$P^i(x,y,t) = \sum_{k=1}^{n_p} \lambda^i_{xyk}\, P_g{}^i(t-\theta^i_{xyk});\ P_g{}^i(\cdot) = \geq o \tag{2}$$

where λ^i_{xyk} is a proportion factor at coordinates (x,y) for event i, and Θ^i_{xyk} is a timing offset at (x,y) for event i. Combining (1) and (2),

$$A_j\, e_j^i(t) = \int_{R_j} F_j\,[\sum_{k=1}^{n_p} \lambda^i_{xyk}\, P_g{}^i(t+\theta^i_{xyk})]\ dR_j \tag{3}$$

Let F_j satisfy the conservative property

$$F_j\,[\sum_{k=1}^{n_p} \lambda^i_{xyk}\, P_g{}^i(t+\theta^i_{xyk})] = \sum_{k=1}^{n_p} \lambda^i_{xyk}\, F_j\,(P_g{}^i(t+\theta^i_{xyk})) \tag{4}$$

(An example of such a loss transform is $F_j(\bullet) = C_j(\bullet)$, where C_j is a constant for R_j.)

The runoff contribution for subarea j is given by

$$q_j^i(t) = \int_{s=0}^{t} e_j^i(t-s)\ \phi_j(s)\ ds = \int_{s=0}^{t}\int_{R_j} \sum_{k=1}^{n_p} \lambda^i_{xyk}\, F_j\,(P_g{}^i(t-\theta^i_{xyk}-s))\ \phi_j(s)\ dR_j\, ds$$

(5)

$$= \int_{s=0}^{t} F_j(P_g^{\,i}(t-s))\, \psi^i_j(s)\, ds \qquad (6)$$

We can introduce nonlinearity with the $\phi_j(\bullet)$ based upon the magnitude of $e_j^i(\bullet)$, such as $\phi'_j(\bullet) = (\phi_j(\bullet) \mid e_j^i(\bullet))$. One method is to define subarea transfer functions according to the severity of storm, i.e., by storm class (e.g., mild, moderate, severe, flooding, etc.). From (6), randomness is inherent in the λ^i_{xyk} and θ^i_{xyk} values, for each storm event i.

Channel Flow Routing

Using a multilinear flow routing analog, without channel losses, (e.g., see Doyle et al., 1983; Becher and Kundzewicz, 1987),

$$Q_{j+1}^{\,i}(t) = q_{j+1}^{\,i}(t) + \sum_{k=1}^{n_r} \alpha_k \; Q_j^{\,i}(t-\beta_k) \qquad (7)$$

where the link is known given nodes j, j+1; node j+1 is downstream of node j, n_r is the number of flow routing translates used in the analog; and the α_k and β_k are constants. The Convex, Muskingum, and many other flow routing techniques are given by (7).

Runoff at node j is given by upstream contributions of runoff

$$Q_j^{\,i}(t) = \sum_{\ell=1}^{n_j} \Big(\sum_{<k>_{j\ell}} \alpha'_{<k>_{j\ell}} q_\ell^{\,i}(t-\beta'_{<k>_{j\ell}}) \Big) \qquad (8)$$

where n_j is the number of subareas tributary to node j; the $<k>_{j\iota}$ is index notation for runoff contributions as summed over index ι, for index k.

Rewriting,

$$Q_j^{\,i}(t) = \sum_{\ell=1}^{n_j} \int_{s=0}^{t} F_\ell(P_g^{\,i}(t-s)) \sum_{<k>_{j\ell}} \alpha'_{<k>_{j\ell}} \psi_j^{\,i'}(s-\beta'_{<k>_{j\ell}})\, ds \qquad (9)$$

$$= \sum_{\ell=1}^{n_j} \int_{s=0}^{t} F_\ell(P_g^i(t-s))\, \Psi_j^{i'}(s)\, ds; \; \Psi_j^{i'}(s) = \sum_{<k>_{j\ell}} \alpha_j{}'_{<k>_{j\ell}} \Psi_j^{i'}(s-\beta'_{<k>_{j\ell}}) \tag{10}$$

Runoff Prediction on a Storm Class Basis

In prediction, the distribution of $P^i(x,y,t)$ is unknown. The possible outcome for runoff, at node j, is a distribution of realizations given by $[Q_j^{*o}(\bullet)]$ where

$$[Q_j^{*o}(t)] = \sum_{\ell=1}^{n_j} \int_{s=0}^{t} F_\ell(P_g^{*}(t-s))\, [\Psi_j^{o}(s)]\, ds \tag{11}$$

where $[\Psi_j^o(s)]$ is the stochastic process of realizations from storm class o, where for node j,

$$[\Psi_j^{o}(s)] = \sum_{<k>_{j\ell}} \alpha^o{}_{<k>_{j\ell}} [\Psi_j^{o}(s-\beta^o{}_{<k>_{j\ell}})] \tag{12}$$

The expectation is given for (11) by

$$E\,[Q_j^{*o}(t)] = \sum_{\ell=1}^{n_j} \int_{s=0}^{t} F_\ell(P_g^{*}(t-s))\, E[\Psi^{o}(s)]\, ds \tag{13}$$

Equation (13) forms a basis of the unit hydrograph procedure commonly used for flood control design and planning.

The Unit Hydrograph Method (Single Area)

The well-known single-area unit hydrograph (UH) method may be developed by the expectation, for the case of prediction of runoff for rainfall event $P_g^*(\bullet)$,

$$E[Qg^{*}(t)] = \int_{s=0}^{t} F(Pg^{*}(t-s))\, E[\Phi(s)]\, ds \tag{14}$$

where $E[Q_g^*(\bullet)]$ is a single runoff hydrograph (usually filtered); and $E[\Phi(\bullet)]$ is the calibrated transfer function. In order for $E[\Phi(\bullet)]$ to be a UH, normalization is needed by letting

$$\eta = \int_{s=0}^{\infty} E[\Phi(\cdot)]\, ds \tag{15}$$

and the UH is simply $\frac{1}{\eta}E[\phi(\cdot)]$

Conclusions and Discussion

Methods have been in use for decades for transferring UH relationships to locations where stream gauge data are not available (for example, see Hromadka et al., 1987). In order to transfer the stochastic relationships of variability in the $[\Phi(\bullet)]$, the same UH transferability techniques may be used. That is, by scaling the distribution of $[\Phi(\bullet)]$ outcomes with respect to $E[\Phi(\bullet)]$, then as $E[\Phi(\bullet)]$ is transferred in UH form, so is the distribution $[\Phi(\bullet)]$. This approach has been implemented in the recent hydrology manuals for the counties of Kern (1992) and the largest county in the mainland United States, San Bernardino (1993). The approach is currently being developed for the hydrology manual of the county of San Joaquin (1993).

References

Becker, A. and Z.W. Kundzewicz
1987 "Nonlinear Flood Routing With Multi-Linear Models." *Water Resources Research* 23:1043-1048.

Bever, K.
1989 "Changing Ideas in Hydrology-The Case of Physically-based Models." *J. Hydrology* 105:157-172.

Doyle, W.H., J.O. Shearman, G.J. Stiltner, and W.R. Krug
1983 "A Digital Model for Streamflow Routing by Convolution Methods." *USGS Water Resources Investigation Report* 83-4160.

Hopper, R.P., A. Stone, E. de Grosbois Christopherson, and H.M. Seip
1988 "Assessing the Birkenes Model of Stream Acidification Using a Multi-signal Calibration Methodology." *Water Resources Research* 24:1308-1316.

Hornberger, G.M., K.J. Bever, B.J. Crosky, and D.E. Sappington
1985 "Shenandoah Watershed Study: Calibration of a Topography-based Variable Contributing Area Hydrological Model to a Small Forested Catchment." *Water Resources Research* 21:1841-1859.

Hromadka II, T.V.
1992 *Hydrology Manual for the County of Kern, California*. Kern County Floodplain Management Division.

Hromadka II, T.V.
1993 *Hydrology Manual for the County of San Bernardino, California*. San Bernardino County Water Resources Division.

Hromadka II, T.V.
1993 *Hydrology Manual for the County of San Joaquin, California*. San Joaquin County Flood Control District.

Hromadka II, T.V., R.H. McCuen, and C.C. Yen
1987 *Computational Hydrology in Flood Control Design and Planning*. Lighthouse Publications.

Hromadka II, T.V., and R.J. Whitley
1989 *Stochastic Integral Equations and Rainfall-Runoff Models*. Springer-Verlag. 384 pp.

Jakeman, A.J., and G.M. Hornberger
1993 "How Much Complexity is Warranted in a Rainfall-Runoff Model?" *Water Resources Research* 29(8).

Loague, K.M., and R.A. Freeze
1985 "A Comparison of Rainfall-Runoff Modelling Techniques on Small Upland Catchments." *Water Resources Research* 21:229-248.

Raines, T.H., and J.B. Valdes
1993 Estimation of Flood Frequencies for Ungaged Catchments. *ASCA, J. HYD. Engineering* 119(10).

TWO-DIMENSIONAL MODELING; A CASE STUDY

Dave Carlton
Kerry Ritland
KCM, Inc.

Introduction

Floodplain maps have been an integral part of the National Flood Insurance Program since its inception. Local officials rely almost exclusively on them to determine whether development is in a potentially hazardous location and subject to floodplain regulations. Almost without exception, the detailed maps produced for riverine flooding have been based upon results produced by one-dimensional steady-state computer programs. The most commonly used of these models are step-backwater models such as the Corps of Engineers' HEC-2 or the Soil Conservation Service's WSP-2 program. When experienced engineers apply these programs properly, they normally provide a good representation of the extent of flooding, depths, and velocities during a selected flood event.

However, in many situations in the State of Washington and elsewhere, results from a one-dimensional model are not a good representation of the actual risk of flooding or severity of the potential hazard. The Nooksack River in Whatcom County in Northwest Washington is one such example. It normally empties into Puget Sound after traveling approximately 80 miles from its headwaters at over 10,000 feet above sea level on Mt. Baker. The last 36 miles of its journey is through a very wide valley where there can be multiple flow paths during major flood events. One of these flow paths is over a low interbasin divide that empties into the Fraser River basin in Canada. During two major floods in November 1990, which were approximately 10- to 25-year events, severe flooding occurred both in Whatcom County and in British Columbia. High water marks from these events have been measured along the lower 30 miles of the river and the overflow into Canada. These flood elevations were in some cases up to six feet higher than those predicted by FEMA for the 100-year event. Other areas that were predicted to be flooded remained dry.

Purpose

The purpose of developing a two-dimensional model of the lower Nooksack River is to create a better set of tools for long-term flood "hazard" management along this reach of the river by Whatcom County. The County and several small communities within the valley no longer want just to react to flood events, but to permanently reduce the hazards and recurring costs associated with them. To help develop a Comprehensive Flood Hazard Management Plan for the Lower Nooksack River, the County formed an advisory committee that reviews all actions and policies associated with flooding within the county. This committee makes recommendations to the County Council for adoption.

The advisory committee and the communities desire to implement a cost-effective combination of non-structural and structural solutions to flood problems that goes beyond the traditional approaches to "flood control" or "floodplain management." With the development of the two-dimensional model and associated maps, the County will have tools to use in making land use decisions, analyzing alternatives and explaining regulatory actions to the public.

Analytical Steps

The first step in the process is to develop 1"=200' scale digital topographic maps with a contour interval of 2 feet. The entire 125 square miles within the potential floodplain of the lower basin has been mapped to this scale using aerial photography. The photos are used not just in the mapping process but also to determine existing land uses. The elevation information is then transferred into a CAD format (Microstation PC) to allow for the electronic development of the finite-element grid system used in the two-dimensional model.

The second step is to develop the finite-element model of the existing river and floodplain topography using the FESWMS-2DH program that was originally developed by the U.S. Geological Survey with assistance from the Federal Highway Administration. The program is a two-dimensional unsteady-state model that can easily handle multiple flow paths and the effect of large storage areas. It uses a finite-element grid system composed of quadrilaterals and triangles. It solves for the depth of flow, direction of flow, and velocity of the flow at each node in the grid system as well as at the center of the element and of each element side. The results of the model can be plotted as water surface elevation contours as well as velocity vectors showing the direction and magnitude of flow. Figure 1 is a plot of velocity vectors along a reach of the Nooksack.

Normally the predicted 10-, 50-, 100-, and 500-year flood events are modeled for FEMA's Flood Insurance Studies. Since the purpose of the Nooksack River model is not to determine zones for insurance, but to analyze existing flow paths and the impacts of alternative solutions on the depth, velocity, and direction of flow, other flows are also being examined. These include the bank-full condition and the 2- and 5-year events.

The model will initially be used to develop inundation, water surface contour, and velocity vector maps for the predicted 100-year flood event, as shown in Figure 1, and other flood frequencies as necessary. Normally, once

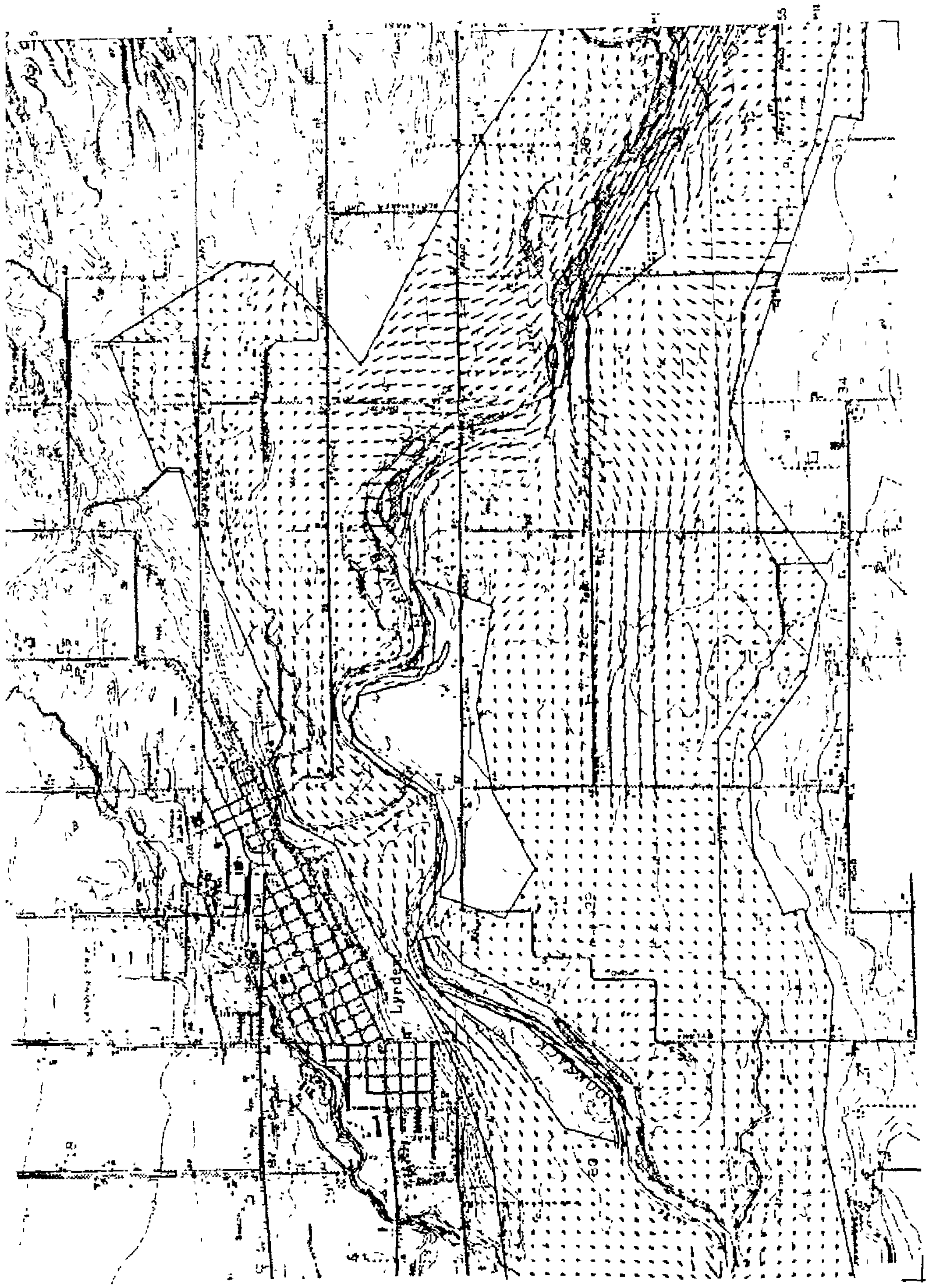

***Figure 1.** Velocity vectors.*

floodplain maps are developed by FEMA they are used to regulate the floodplain and floodway without modification. In our case the maps will be used to assist the advisory committee and County Council when making decisions concerning land use, mitigation sites, regulations, and structural alternatives.

Decisionmaking

The decisionmaking process for the completion of the comprehensive plan will begin with deciding which areas that currently flood should always be allowed to flood. These areas will be selected based upon the occurrence of high flow velocities, depth of flooding, frequency of flooding, potential for channel migration, historical channel location, and current land use. Once these areas are designated we will use the two-dimensional model to determine the impacts on the rest of the floodplain of allowing development. For this analysis we will assume that all land not designated for flooding will be completely filled to the flood-protection elevation with no compensatory storage required, or will be protected by an adequate levee. The results of this model run will be compared with the existing conditions model to determine the impacts of allowing the development. A two-dimensional model is essential for this analysis due to the multiple flow paths within the floodplain.

The anticipated impacts of new development include increased depths and frequency of flooding in locations upstream and downstream of the allowed developments, increased flow velocities, and potentially increased overflows into Canada. As an example of how two-dimensional modeling can predict the impacts of floodplain filling, a section of the floodplain in Figure 1 was removed from the model. The resulting impacts of the filling are shown as contours of water surface elevation in Figure 2. Thus, incremental changes in flood elevations and velocity can be determined easily at any point within the floodplain.

These impacts will be discussed with the committee to determine whether they and any required mitigation are acceptable. If not, the model will be revised until an acceptable level of impact is obtained. One of the most important questions the committee will be dealing with is equity. What price is the community willing to pay to allow some of the land to be protected from flooding, or filled to above the flood elevation? The answer to this question once the community is presented with the impacts of its desired actions will be very interesting. For example, much of the area outside of the cities and within the floodplain is currently used for agriculture. The County has placed a very high priority on the preservation of these lands for agricultural uses. Therefore, while there is little desire for any changes in land use, there is, for example, a definite desire to allow existing dairymen to construct critter pads, which are filled areas for cattle to congregate on during a flood. One facility by itself has little impact, but if 30 or 40 critter pads are built along 10 miles of the river a significant impact may occur. If so, is that acceptable to everyone who is impacted?

Another issue will be the interbasin overflow to Canada. Any increase in current levels of overflow will be unacceptable, or must be mitigated to everyone's satisfaction. Other more common issues concern the protection of

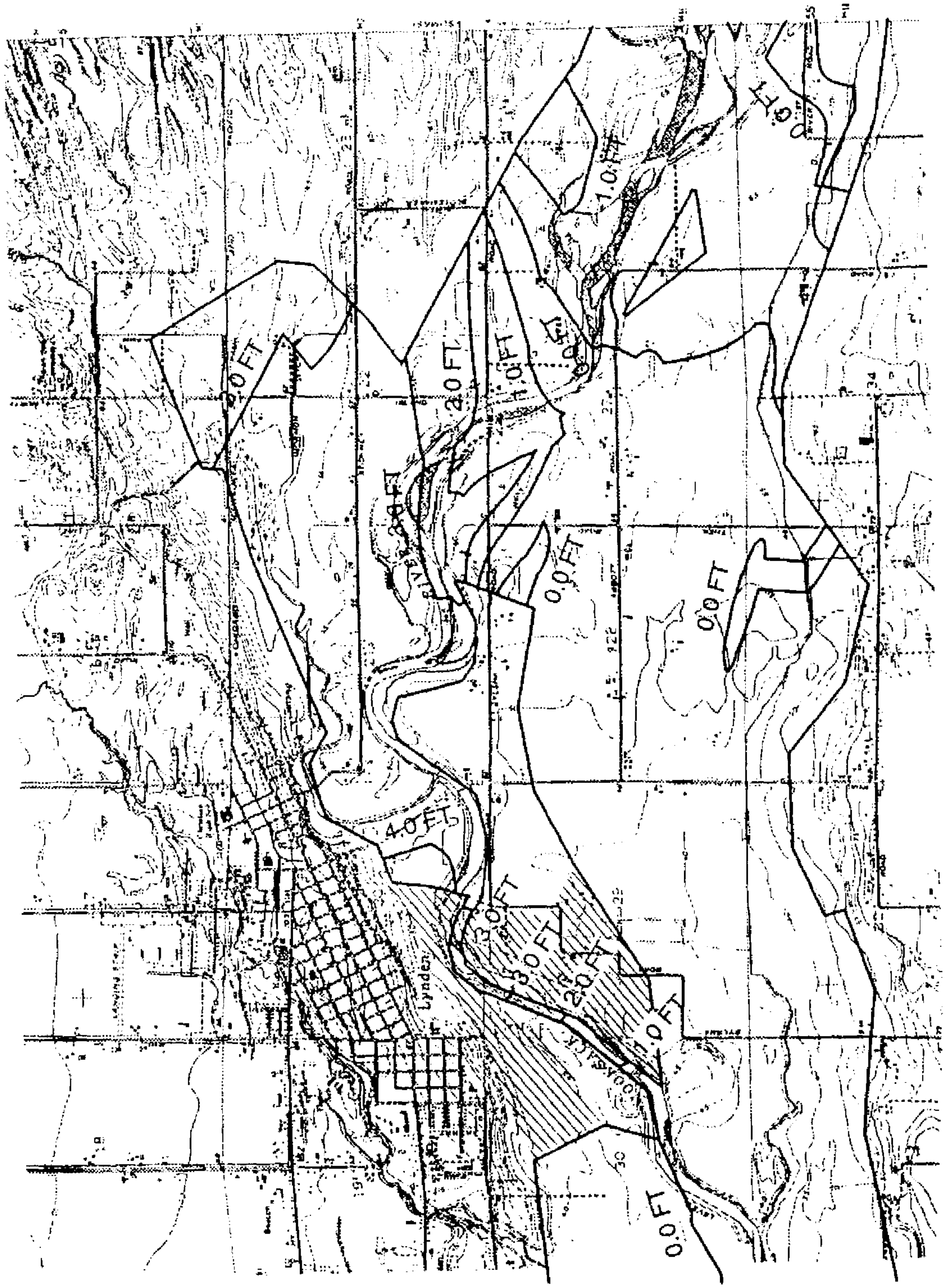

Figure 2. Water surface changes.

existing development in the cities of Ferndale, Lynden and Everson. If these areas are no longer allowed to flood through the construction of levees, what impact will that have on flood velocities and flow paths?

Results

The results of the two-dimensional modeling will be used by local officials in conjunction with other environmental, engineering, and economic studies to predict the impact of potential structural projects along the river and develop a comprehensive management plan for the Lower Nooksack River that will minimize the hazards in a manner acceptable to the citizens of the county. A new set of management policies and regulations will be developed to implement the desires of the county and minimize flood hazards. These will include the prohibition of new structures in areas shown by the model to be hazardous (i.e., the floodway) and potentially the requirement of compensatory storage in areas where storage volumes are critical, but development can be allowed. Also, by showing the existing velocity and depth of flow over roads and driveways, the requirement for dry land access to all new development may become more acceptable. By using this model and deciding where development is desirable and permitted, there will be no encroachment on needed conveyance or storage capacity. It will be an informed community decision instead of one that is perceived to be handed down from the state or federal governments.

Conclusions

The principle advantages of using two-dimensional modeling for floodplain analysis are the ability to accurately simulate complex flow patterns, such as split flows; to determine flood hazards at any point within the floodplain in terms of water depth, direction, and velocity; and to evaluate the impacts of potential flood hazard management measures. Conventional one-dimensional floodplain modeling is not capable of such tasks in the case of the Nooksack River. The 100-year floodplain maps developed using the two-dimensional modeling will better represent the actual risk of flooding than do FEMA's existing maps for the river. They will be submitted to FEMA, along with the management plan and accompanying regulations, to show compliance with the NFIP in Whatcom County. The maps can also be used to show the locations where flood insurance is required. The new standards will help to increase the County's standing in the Community Rating System program and reduce flood insurance premiums for its residents.

AUTOMATED HEC-2 MODELING USING CAD

Chris E. Maeder
BOSS International Corporation

Introduction

Computer-aided drafting (CAD) software has been used for many years to speed up and automate the tedious and mundane tasks involved in drafting, updating, and maintaining architectural and engineering drawings. Recent advances in CAD software have provided "hooks" in which customized programming can be linked with off-the-shelf CAD software. This enables development of customized engineering CAD applications. These special purpose CAD applications can eliminate some of the tedious and mundane tasks involved with engineering, analysis, and design, in the same fashion as CAD has done with drafting. Replacing these manual tasks with automated processes, CAD can improve both the speed and quality of the entire engineering process.

Using AutoCAD and ADS (AutoCAD Development System) programming, we have developed an application (BOSS HEC-2 for AutoCAD) that automates most of the tasks associated with HEC-2 water surface profile modeling.

Development of this application started in the spring of 1989, after recognizing a need to marry CAD technology with our existing hydraulic and hydrologic engineering software. The application was first released as a commercial product in January 1992. Continued improvements, enhancements, and updates have been added to the application since then.

Key concerns during development of this application were its ease of use, functionality, and analysis output.

Ease of Use

An important concern during the development of this application was ease of use. We wanted an engineer to be able to use the product easily with little or no AutoCAD training. To do this, easy-to-use menus and straightforward data entry dialog boxes were developed to allow an engineer to quickly become proficient at using this application for performing HEC-2 modeling. To further improve ease of use, all data input, analysis, review of analysis results, and output of results is performed from within the AutoCAD interface.

Functionality

Early during development, the following features were identified to provide maximum functionality to the engineer.

1. Support for all HEC-2 features, including:

Special Bridge	Normal Bridge
Special Culvert	Split Flows
Floodplain Encroachments	Channel Improvements
Subcritical Flow	Supercritical Flow
Imperial Units	Metric Units

2. Importation of all types of HEC-2 models, using either fixed format or free format card files.

3. Exportation of HEC-2 card files.

4. Data input to be as flexible as possible, including:

   - Cut cross-sections by simply drawing a line across a 3-D digital topo map, with contour elevations automatically determined.

   - Cut cross-sections from either a paper topo map, 2-D digital topo map, or 3-D digital topo map.

   - Topo map not required, but can be added at any time to the model if desired.

   - Import cross-sections from multiple HEC-2 files, XYZ point files, and station elevation files.

   - Construct a cross-section by stitching together data from multiple sources.

   - Automatic cross-section ground point reduction using published FEMA methodology (Federal Emergency Management Agency, 1993).

   - Quick computation of Normal Q, Normal WSEL, Critical Q, and Critical WSEL for any cross-section.

5. System to be fast.

6. Use of a rule-based expert system to check the HEC-2 data for modeling errors and potential problems.

7. Allow several HEC-2 models to be defined, maintained, and supported within a single AutoCAD drawing.

8. Allow user-assisted linking of pre-existing HEC-2 data sets to topo maps, thereby allowing a pre-existing HEC-2 model and its analysis results to be displayed on a topo map of the region being studied.

Analysis Output

Once a HEC-2 analysis has been performed, output results are easily displayed on the cross-sections. Single or multiple profiles can be displayed on the same cross-section plot, with complete control over scale, grid size, axis graduation, line styles, and line colors.

Profile plots can be created at any time—even before running the analysis. However, output results can only be displayed after an analysis has been performed.

A method of automatically creating fixed size profile plots was devised. This allows profile plots for long river studies to be quickly created.

Complete control over profile plot scale, grid size, axis graduation, line styles, line colors, and line symbols is provided. Single or multiple profiles can be displayed on the same profile plot. Plotting multiple profiles on the same profile plot helps the engineer compare results from different flow discharges.

All bridge, culvert, and roadway structures can be displayed on the profile plots. This aids the engineer, for example, in determining for which discharges a particular bridge structure begins to experience pressure flow.

Flood inundation maps can be quickly created, displaying the edge of water stationing on the topo map cross-section cuts. Straight lines are used to connect the edge of water stationing between cross-sections. The edge of water line can be easily stretched and shaped by the user to follow the ground topography. Additional tools are provided to help draw floodplain boundaries.

Future Enhancements

Further automation in this application is desired. The following capabilities have been identified and are being investigated.

Integrated Surface Modeling using DTM Technology

Integration of our AutoCAD Digital Terrain Modeler (BOSS DTM for AutoCAD) and our AutoCAD HEC-2 application is planned. Integration of these two applications will enable surface intersection techniques to automatically map the edge of water for river reach regions between the specified cross-sections, using the topo map ground topography and water surface.

GIS Interface

Linkage with a geographical information system (GIS) will further automate HEC-2 modeling, by automating the retrieval and updating of floodplain mapping information. A GIS can be used as the underlying data source to this application, vastly speeding up and simplifying the data retrieval tasks for creating, updating, and maintaining floodplain maps. Linkage with ESRI ArcCAD GIS is being investigated.

For the past year, the Wisconsin Department of Natural Resources (Lulloff, 1994) has been using this AutoCAD HEC-2 application and ESRI ArcInfo GIS in a pilot project to demonstrate the feasibility of automating the tasks associated with updating and maintaining flood inundation maps using a GIS.

Conclusion

Recent advances in CAD software have provided opportunities to automate many aspects of engineering. In this paper we have shown one such application, integrating HEC-2 and AutoCAD to automate water surface profile modeling.

References

Federal Emergency Management Agency

1993 "Examples of Cross Section Ground Point Spacing," Figure A4-3. Page A4-12, *Guidelines and Specifications for Study Contractors*. FEMA-37. Washington, D.C.: FEMA.

Lulloff, Al

1994 Personal communication. Wisconsin Department of Natural Resources, Division of Water Regulation and Zoning, Madison, Wisconsin.

THE USE OF HEC-2 FOR FLOOD INSURANCE STUDY REVISIONS: PROBLEMS AND HOW TO AVOID THEM

Joseph B. Chapman and Moe Khine
Dewberry & Davis

Introduction

HEC-2 is the most common step-backwater program used for preparing and revising Flood Insurance Studies (FISs) for the Federal Emergency Management Agency (FEMA). HEC-2 is also the most versatile federally developed computer program available to calculate one-dimensional, gradually varied flow in channels. This versatility is reflected in the large variety of options that can be selected in the job control and other various records in HEC-2. However, it is because of this versatility that the use of one or a combination of the various methods can lead to inconsistent results between HEC-2 analyses for the same reach of stream. The National Flood Insurance Program (NFIP), administered by FEMA, aims to provide a consistent set of criteria by which to establish base (100-year) flood elevations and sound floodplain management criteria. Often because of the multitude of options available in HEC-2, inconsistencies can occur that make it difficult for individuals submitting FEMA map revision requests to do so in an efficient, accurate manner. Inconsistent application of these options may result in processing delays and ultimate rejection of revision requests due to technical inadequacies or apparent non-compliance with NFIP regulations.

Issues

Use of NH Records

NH records are used to define Manning's roughness coefficients, "n" values, for an individual cross section that has varying channel and/or overbank "n" values. When an NH record is used to define multiple "n" values within the defined channel, problems may occur when attempting to perform a floodway run. Specifically, when multiple channel "n" values are used, the HEC-2 program computes a composite channel "n" value if both channel bank side slopes are steeper than 5:1 (horizontal to vertical). In the case of a floodway run, although a composite "n" value is not computed for the 100-year natural profile, the program will compute a composite "n" value for the encroached profile if the encroachment stations are at the channel bank stations. For the encroached profile, the program computes a different side slope based on the artificially high elevation of the encroachment station. This may result in a higher surcharge value that is unrealistic.

Shifting the encroachment station using Method 1 by one foot to ensure that the station is not coincident with the channel bank station will eliminate this problem. By making this change, the HEC-2 program will not compute a composite channel "n" value for the encroached profile. This approach will not interfere with the capability of the HEC-2 program to compute the composite "n" value when the side slopes are actually steeper than 5H:1V for the channel portion.

Use of HVINS

The HEC-2 program contains an option that computes interpolated cross sections when the velocity head difference between consecutive cross sections is greater than the amount specified on field seven of the J1 record. Use of this option can result in problems during both a multiple profile run or a floodway run. Specifically, the program will compute a different number of interpolated cross sections for each profile, and may result in problems in developing consistent water surface elevations in multiple profile runs and encroachments in a floodway run. For the purpose of FIS revisions, it is not recommended that the HVINS option be used. If necessary, additional cross sections should be input using additional X1 records into the HEC-2 model to properly model the flow conditions.

Bridge Encroachment Option

For performing floodway runs, the HEC-2 program has various encroachment methods. The most widely used are Method 1, where encroachment stations are manually input, and Method 4, where encroachment stations are computed based on equal conveyance reduction method. In either case, the standard encroachment specified on the ET records in the HEC-2 model, by using 10.4 or 7.1 for example, does not consider proper encroachments at structures subject to weir flow. In those cases, an additional option available in the HEC-2 program known as the bridge encroachment option should be utilized.

This can be done by adding a value of .01 to the code describing the encroachment method (e.g., 10.41 or 7.11). This enables the program to encroach properly on the weir flow area over the road profile such that proper flow distribution is achieved from the downstream section, through the road profile, to the upstream section. Encroachment of the road profile does not imply that the road will be filled outside the encroachment stations. Since the floodplain at the upstream and downstream sections can be filled up to the encroachment stations, the effective flow area over the roadway is limited to the area between the encroachment stations.

Use of the bridge encroachment option should not impact encroachment computations for bridges not subject to weir flow. Consequently, it is a good practice to always add .01 to the code describing the method of encroachment at all structures to eliminate the possibility of the incorrect encroachment.

Special Bridge Modeling

The HEC-2 model utilizes several procedures to compute low flow through structures (bridge and culvert) using the Special Bridge methodology. Two types of flows that can cause problems are Class A and Class B low flows. Classification of Class A and Class B low flows are based on the momentum principle. For a subcritical profile run, if the flow through the structure is also subcritical, the flow type is classified as Class A low flow; if the flow through the structure is supercritical, the type of flow is classified as Class B low flow. For Class A low flow the upstream water surface elevation is computed by adding the losses through the structure, using Yarnell's equation, to the downstream water surface elevation. For Class B low flow the upstream water surface elevation is determined based on the critical momentum within the structure.

Generally the losses through the structure computed using Yarnell's equation are small. Therefore, upstream water surface elevations for Class A low flow conditions can be lower than upstream water surface elevations computed using Class B low flow. This can cause significant problems in analyzing the impact of bridge/culvert projects for compliance with NFIP regulations.

In one particular instance a proposed bridge structure was analyzed using Special Bridge and the analysis determined the flow type to be Class A low flow. This analysis indicated that the structure did not result in increases in 100-year water surface elevations greater than those allowed under NFIP regulations. Subsequently, when the project was completed, information was submitted in support of a revision to the NFIP maps. As part of construction of the bridge, downstream channel modifications were undertaken that resulted in slight decreases in downstream water surface elevation over those indicated in the proposed analysis. This slight reduction in downstream water surface elevation resulted in a change in flow type from Class A low flow to Class B low flow. The losses through the bridge structure computed for Class B low flow were higher than those computed at the proposed stage under Class A low flow. As a result the analysis of the completed bridge reflected increases in water surface elevation greater than those allowed under NFIP regulations.

One solution to avoid this problem is to use Normal Bridge method for analyzing low flow through structures.

Options for Selecting Friction Loss Computation

The HEC-2 program utilizes the average conveyance equation as the default option for computing the friction slope. The use of the J6 record also allows a user to choose one of the following three friction slope equations: average friction slope, geometric mean friction slope, and harmonic mean friction slope. The use of a value of 1.0 in field 1 of the J6 record will prompt the HEC-2 program to select a friction slope on a reach by reach basis from one of the three optional methods listed above, but not the default option of using the average conveyance equation. There are several problems that arise when allowing the program to choose the friction slope method on a reach by reach basis.

1. Most streams studied using HEC-2 in FISs use the default method of average conveyance equation. Any revisions using one of the other methods will produce inconsistent results.

2. When a value of 1.0 is input in field 1 of the J6 record, the program selects the friction slope method based on flow conditions. For a floodway run, flow conditions for a particular reach in the 100-year natural profile can be different from the flow conditions in the same reach for the encroached profile. This can result in unacceptable surcharge values due solely to these varied methodologies.

3. When analyzing the impacts of any floodplain modification projects, any changes in flow conditions could yield varying results for pre- and post-project conditions. Increases in 100-year water surface elevations could then be incorrectly attributed to the construction of the project and result in an incorrect determination.

The HEC-2 manual does not provide specific guidance concerning which method is more correct. However, use of the default (average conveyance friction slope) option will ensure the most consistent results for the purposes of requesting a revision to NFIP maps.

Conclusion

The HEC-2 program has different options to analyze water surface profiles. Selection of the proper options is essential in obtaining consistent and accurate determination of water surface elevations for NFIP purposes. Additional research should be performed for areas where the selection of a particular option is unclear.