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Measurement of liquid flow in open channels — Computing stream flow using an unsteady flow model

Mesure de débit de liquides dans les canaux découverts — Calcul de l'écoulement dans un cours d'eau à l'aide d'un modèle d'écoulement non permanent

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 11627, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 113, *Hydrometric determinations,* Subcommittee SC 1, *Velocity area methods.*

This document is being issued in the Technical Report (type 2) series of publications (according to subclause G.3.2.2 of part 1 of the ISO/IEC Directives) as a "prospective standard for provisional application" in the field of hydrometric determinations because there is an urgent need for

guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the ISO Central Secretariat.

A review of this Technical Report (type 2) will be carried out not later than three years after its publication with the options of: extension for another three years; conversion into an International Standard; or withdrawal.

Measurement of liquid flow in open channels — Computing stream flow using an unsteady flow model

1 SCOPE

This Technical Report describes a method for computing continuous records of stream flow in an open channel through the numerical solution of the one-dimensional unsteady flow equations. Such an approach is typically identified as an unsteady flow model and generally involves the use of computers for solution of the flow equations.

Unsteady flow models are appropriate for computing stream flow records at locations where (1) a single-valued stage-discharge relation does not exist, (2) backwater affects the discharge under selected or all conditions, (3) flows are affected by tides, or (4) it is not possible to gage the flow using velocity-area methods. Unsteady flow models also are appropriate for evaluating the effects of changes in a managed flow regime on downstream conditions prior to the implementation of any changes.

This Technical Report is applicable to steady and unsteady flows, to nominee flows, and to tidal flows in which there are no significant longitudinal and vertical density gradients. The method is considered equivalent to, or better than, the commonly used stage-fall-discharge technique (ISO 1100-1:1996, 7.2 and Annex C) because the method uses information on the physical characteristics of the channel, including the cross-sectional geometry, channel rugosity and channel slope, and the method is based on a mathematical description of the physics of fluid flow.

This Technical Report describes the theoretical basis and fundamental assumptions of the technique, and provides a summary of selected numerical methods used to solve the unsteady flow equations. Also provided are details on the application of an unsteady flow model, including data requirements, procedures for model calibration, testing, and applications, and identification of uncertainties associated with the method. This Technical Report does not provide sufficient information for the development of a computer program for solving the unsteady flow equations, but rather is based on the assumption that an adequately documented computer program is available

2 REFERENCES

ISO 748:1997, *Measurement of liquid flow in open channels — Velocity-area methods*.

ISO 772:1996, *Hydrometric determinations — Vocabulary and symbols*.

ISO 1070:1992, *Liquid flow measurement in open channels — Slope-area method*.

ISO 1100-1:1996, *Measurement of liquid flow in open channels — Part 1: Establishment and operation of a gauging station*.

ISO 1100-2:—[1]), *Measurement of liquid flow in open channels — Part 2: Determination of the stage-discharge relation*.

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1) To be published. (Revision of ISO 1100-2:1982)

ISO 2425:—[2]), *Methods for hydrometric measurements under tidal conditions*.

ISO 2537:1988, *Liquid flow measurement in open channels — Rotating element current-meters*.

ISO 3454:1983, *Liquid flow measurement in open channels — Direct depth sounding and suspension equipment*.

ISO 4373:1995, *Measurement of liquid flow in open channels — Water-level measuring devices*.

ISO 6416:1992, *Measurement of liquid flow in open channels — Measurement of discharge by the ultrasonic (acoustic) method*.

ISO 9555-1:1994, *Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow — Part 1: General*.

ISO 9555-2:1992, *Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow — Part 2: Radioactive tracers*.

ISO 9555-3:1992, *Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow — Part 3: Chemical tracers*.

ISO 9555-4:1992, *Measurement of liquid flow in open channels — Tracer dilution methods for the measurement of steady flow — Part 4: Fluorescent tracers*.

3 DEFINITIONS

For the purposes of this Technical Report, the definitions given in ISO 772 and the following definitions apply.

3.1 Boundary condition: A boundary condition is a condition that a dependent variable of a differential equation must satisfy along the boundary of the model domain. Boundary conditions for the dependent variables must be specified at the physical extremities of the modeled region for the duration of model application.

3.2 Courant condition: The usual condition for the numerical stability of the explicit formulation of a numerical scheme which requires that the ratio of the propagation speed of a physical disturbance to that of a numerical signal should not exceed unity.

3.3 Explicit finite-difference numerical scheme: Explicit numerical schemes convert either the characteristic equations or the governing equations to a system of linear algebraic equations from which the unknowns may be solved directly (explicitly) without iterative computations. Dependent variables on the advanced time level are determined one point at a time from known values and conditions at the present or previous time levels. Explicit schemes are only conditionally stable, meaning that errors may grow as the solution progresses, and the errors are a function of the time and distance finite-difference step sizes. Explicit schemes are generally stable when the courant conditions is met, which results in limitations on the distance step and maximum time which can be used.

3.4 Gradually-varied, unsteady flow: Generally nonuniform flow in which there are no abrupt changes in depth along the longitudinal axis of the channel, and in which depth (and velocity and discharge) change with time.

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2) To be published. (Revision of ISO 2425:1974)

3.5 Hydrograph: A relation in graphical, equational, or tabular form between time and flow variables such as discharge, depth, velocity, and stage. Stage and dischar   hydrographs are typically used for open channel flows.

3.6 Implicit finite-difference numerical scheme: Implicit numerical schemes convert either the characteristic equations or the governing equations to a system on nonlinear algebraic equations from which the unknowns must be solved iteratively. All of the unknowns within the model domain are determined simultaneously, rather than point-by-point as with explicit methods. Implicit methods are generally stable, and are more computationally efficient than explicit schemes, but implicit schemes require more complex computer algorithms than do explicit schemes.

3.7 Initial conditions: A description of the dynamic conditions (typically discharge and depth of flow for unsteady flow models) in the model domain at some specified time, usually the beginning of the simulation period. For all subsequent times, the governing equations and the boundary conditions describe the state of the system.

3.8 Method of characteristics: The method of characteristics is a mathematical approach for solving boundary-value problems by transforming the original partial differential equations representing the physical system into corresponding characteristic equations. The characteristic equations are ordinary differential equations and generally are more amenable to numerical solution than are the original partial differential equations.

3.9 Momentum coefficient: The momentum coefficient, also known as the Boussinesq coefficient, quantifies the deviation of the velocity at any point in a cross section from uniform velocity distribution in the same cross section. A value of unity indicates that a uniform velocity distribution is present in the cross section. The momentum coefficient generally varies between about 1.01 and 1.12 for fairly straight, prismatic channels; coefficients are typically smaller for large, deep channels than for small channels.

4 UNITS OF MEASUREMENT

The units of measurement used in this International Standard are SI units.

5 PRINCIPLES OF UNSTEADY FLOW MODELS

5.1 Governing equations

The foundations for the fundamental derivation of the governing one-dimensional unsteady flow equations were laid by the 19th century hydraulicians Coriolis, Boussinesq, and Saint Venant. The

governing equations are the one-dimensional, cross-sectionally averaged expressions for (1) the conservation of mass (or equation of continuity),

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

and, (2) conservation of linear momentum

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right) + gA\frac{\partial z}{\partial x} + gA(S_f - S_o) = qu' \tag{2}$$

where:

A is the cross-sectional area of the channel, and varies with x, t, and z;

t is time;

Q is the discharge, and varies with x and t;

u' is longitudinal component of the lateral inflow velocity, and varies with x and t;

x is the longitudinal position along the channel axis;

z is the depth of flow, and varies with x and t;

g is the acceleration of gravity;

β is the momentum coefficient, and varies with x, z, and t;

q is the lateral inflow per unit length of channel, and varies with x and t;

S_o is the bed slope, and varies with x; and

S_f is the friction slope, and varies with x, t, and z.

The momentum coefficient may be computed as

$$\beta = \int\frac{u^2 dA}{U^2 A} \tag{3}$$

where:

u is the velocity in some elemental area dA, and

U is the mean velocity in the same cross section having a total area A.

The friction slope, S_f, accounts for the resistance due to external boundary stresses. The friction slope is generally written as

$$S_f = \frac{Q|Q|n^2}{AR^{4/3}} \tag{4}$$

where

R is the hydraulic radius, and

n is the Manning coefficient.

4

Both R and n can vary as a function of x, z, and t. Equation 4 is based on the assumption that the Manning equation for steady, uniform flow provides a reasonable approximation for S_f in unsteady, nonuniform flow.

Equation 2 can be modified to include a term accounting for the momentum imparted to the water by a temporally and spatially varying wind. Equations 1 and 2 also can be written with (1) depth and velocity, (2) stage and velocity, or (3) stage and discharge as the dependent variables.

Equations 1 and 2 apply to the unsteady, spatially-varied, turbulent free-surface flow of an incompressible, viscous fluid in an open channel of arbitrary cross section and alignment. The equations are solved simultaneously for the unknowns z (depth of flow) and Q (discharge) as a function of time (t) and longitudinal position (x).

5.2 Assumptions upon which governing equations are based

Equations 1 and 2 are derived from first principles, and may be obtained directly from the three-dimensional equation of mass continuity and the Navier-Stokes equations, which are general, three-dimensional statements of the conservation of momentum for any fluid flow. A number of assumptions are required to derive equations 1 and 2. An unsteady flow model which is based on equations 1 and 2 should generally be applied to those conditions in which none of the major assumptions are severely violated. The assumptions are as follows.

- The flow is approximately one-dimensional, meaning that the predominant spatial variation in dynamic conditions (discharge, velocity, and stage) is in the longitudinal direction.
- The fluid density is homogeneous throughout the modeled reach.
- Vertical accelerations are negligible (the hydrostatic pressure distribution is applicable).
- Velocity is uniformly distributed in a given cross section. Inclusion of the momentum coefficient in equation 2 allows this assumption to be violated somewhat, but there should be no flow separation, and streamline should not be highly curvilinear.
- Neither aggradation nor degradation of the flow channel occurs.
- Turbulence and energy dissipation can be described by resistance laws formulated for steady, uniform flow (required for equation 4).
- There are no abrupt changes in channel shape or alignment.
- The velocity is zero at the channel boundary.
- There is no superelevation of the water level at any cross section.
- Surface tension and the density of air at the free surface are negligible.

5.3 Simplified models

A number of techniques have been used to simplify equations 1 and 2 to provide approximate unsteady flow models. These simplified models generally provide results with less computational

effort and fewer data than is required for solution of the full equations. However, the models have limited applicability, and it is more appropriate to use a general unsteady flow model based on equations 1 and 2 to obtain reliable records of discharge under a wide range of conditions. A brief summary of simplified models follows.

5.3.1 Empirical models

Empirical models are based on observations of past flood events. These models are limited to applications in which sufficient observations of inflows and outflows of a river section are available to calibrate essential empirical relations or routing coefficients. These models are typically applied to slowly fluctuating rivers with negligible lateral inflows and backwater effects.

5.3.2 Hydrologic models

Hydrologic models are based on the continuity equation written as

$$I - O = dS/dt \qquad (5)$$

where

I is the inflow to the modeled river section;
O is the outflow from the section; and
dS is the change in storage within the section during the time interval dt.

The storage is generally assumed to be related to the inflow or outflow by some empirically-determined storage constant. Hydrologic models are limited to applications in which the stage-discharge relation is single-valued, and are not applicable to flows having backwater effects, significant lateral inflows, or looped stage-discharge relations. Difficulties in solving equation 5 are often encountered when flows are changing rapidly with time.

5.3.3 Linearized models

Linearized models are derived from equations 1 and 2 by ignoring or linearizing nonlinear terms in the equations. The linearized equations can then be analytically integrated with less computational effort than is required for numerical integration of equations 1 and 2. The most common simplifying assumptions for these models are:

- the acceleration term (second term) in the momentum equation (equation 2) is negligible;
- the cross-sectional area (A) and channel bottom slope (S_o) are constant;
- the friction slope (S_f) is linearized with respect to discharge and depth;
- there is no lateral inflow; and
- the routed flood wave has a simple shape described by an analytical expression.

These assumptions severely limit the applicability of linearized models.

5.3.4 Kinematic wave model

The kinematic wave model is derived by assuming that all terms in the momentum equation are negligible relative to the friction slope (S_f) and the bed slope (S_o), and that there is no lateral inflow,

so that

$$S_f = S_o \tag{6}$$

As a consequence of equation 6, the discharge for a kinematic flow is equal to the normal discharge. This means that the momentum of the unsteady flow is described by an expression, such as the Manning or Chezy equations, in which flow is a single-valued function of depth of flow. Moreover, kinematic waves travel without attenuation of the peak flow, but the shape of the flood wave is modified as the wave is translated downstream. The kinematic wave model allows only the downstream propagation of flow disturbances, so that backwater and tidal effects cannot be modeled. Numerous analytical solutions exist for applications of the kinematic wave model to specific flow geometries, and these models are most widely used in the routing of overland flow of precipitation runoff.

5.3.5 Diffusion analogy model

The diffusion analogy model is obtained by assuming that the channel is prismatic, that the local and convective acceleration terms in the momentum equation are negligible, and that there is no lateral inflow. The continuity and momentum equations may then be combined to form a single parabolic partial-differential equation, which is in the form of the so-called convective-diffusion equation with the single unknown of discharge. The local and convective acceleration terms, the first two terms in equation 2, are often small in steep streams.

The diffusion analogy model can be used to compute flows affected by backwater conditions. However, the diffusion model is limited to applications in which flows change relatively slowly, and in which the channel has a rather uniform geometry throughout the modeled reach

5.4 Numerical techniques for solution of governing equations

No known analytical solutions exist for equations 1 and 2. Consequently, numerical techniques are used to convert equations 1 and 2 into algebraic equations that may be solved for z and Q at finite, incremental values of x and t. This solution depends on the proper description of the cross-sectional area as a function of x and t, and on the availability of accurate boundary condition data.

A variety of numerical techniques have been proposed and used to solve the unsteady flow equations. Although finite element methods may be used to solve the equations, finite-difference techniques generally are more appropriate for the solution of the one-dimensional partial-differential equations describing unsteady open-channel flow. The three broad categories of numerical techniques are (1) method of characteristics, (2) explicit finite-difference methods, and

(3) implicit finite-difference methods. Numerous variations of each of these general categories of techniques exist. The methods are briefly reviewed to provide some perspective on advantages and disadvantages of each method.

5.4.1 Method of characteristics

The method of characteristics is a mathematical approach for solving boundary-value problems by transforming the original partial differential equations representing the physical system into corresponding characteristic equations. In this context, the characteristic is the speed of a wave relative to a stationary observer. Characteristic equations are ordinary differential equations and generally are more amenable to numerical solution than the original partial differential equations. The characteristic equations are solved using either explicit or implicit finite-difference methods.

The method of characteristics can be used with a curvilinear grid or a rectangular grid in the x-t domain. The curvilinear grid generally is not used for solution of the unsteady flow equations in natural open channels. The nature of characteristics is such that the wave trains in the x-t domain usually are not orthogonal, so solutions of the characteristic equations typically do not coincide with a point on the rectangular grid representing the natural system. Consequently, an interpolation scheme is required to transfer results from the characteristic network to the rectangular grid representing the flow system. The accuracy of the interpolation scheme plays a major role in determining the performance of the method of characteristics in solving the governing equations.

5.4.2 Explicit finite-difference methods

Explicit numerical schemes convert either the characteristic equations or the governing equations to a system of linear algebraic equations from which the unknowns may be solved directly (explicitly) without iterative computations. Dependent variables on the advanced time level are determined one point at a time from known values and conditions at the present or previous time levels. Explicit schemes are only conditionally stable, meaning that errors may grow as the solution progresses, and the errors are a function of the time and distance finite-difference step sizes. Explicit schemes are generally stable when the Courant condition is met, which results in limitations on the distance step and maximum time which can be used.

In order to meet numerical stability requirements, the computational time step must decrease as the hydraulic depth increases. Consequently, computational time steps may be required to be on the order of a few minutes for unsteady flow models of large rivers, which makes the models somewhat computationally inefficient. Explicit finite-difference schemes also require that the computational distance steps be equal throughout the model domain, which may be a disadvantage for some systems.

5.4.3 Implicit finite-difference methods

Implicit numerical schemes convert either the characteristic equations or the governing equations to a system on nonlinear algebraic equations from which the unknowns must be solved iteratively. Consequently, a system of 2N algebraic equations is generated for a model having N cross sections along the x-axis. All of the unknowns within the model domain are determined simultaneously, rather than point-by-point as with explicit methods.

Weighting factors are typically required in the application of implicit schemes. These factors determine the time between adjacent time levels at which (1) the spatial derivatives and (2) functional quantities are evaluated; functional quantities are such features as cross-sectional area, top width, and hydraulic radius, all of which are functions of the computed depth of flow. Some judgement is required in selecting these weighting factors, and the weighting factors often are adjusted as part of the model calibration process. The accuracy of the numerical scheme generally decreases as the factor approaches one, where the terms in the governing equations are expressed entirely in terms of the future time step.

Fewer numerical stability problems are encountered with implicit schemes than with explicit schemes. Numerical instabilities can occur when modeling rapidly varying flows if the time step is large and if the spatial derivatives are not sufficiently weighted toward the future time step. Nonlinearities caused by irregular cross sections having widths that vary rapidly along the channel or with depth also can cause numerical instabilities in implicit models.

6 DATA REQUIREMENTS

Data are required to construct, calibrate, test, and apply unsteady flow models. Referenced International Standards for the measurement of velocity and discharge, and for collection of water-level and discharge records should be followed.

In general, data are required at model boundaries for the entire period for which flow is to be computed using the unsteady flow model. Short-term records and discrete measurements are needed at locations within the model domain for the period which is used for model calibration and testing.

6.1 Selection of model boundaries

Reliable, accurate, and appropriate boundary condition data are required for successful computation of streamflow using an unsteady flow model. Model boundaries must be selected prior to the installation of data-collection instrumentation. Boundaries should be in locations where there are a minimum of flow disturbances, such as sharp bends, rapid changes in cross-sectional geometry, and major inflows. The modeled reach length also should be sufficiently long to permit accurate determination of the longitudinal water-surface slope so that adverse effects of measurement errors are minimized. Moreover, as subsequently discussed, discharge records

should be used as the upstream boundary condition if at all possible. For these reasons, it may be expedient to extend the model domain beyond the reach for which streamflow computations are actually needed in order to obtain the necessary data for model boundary conditions.

6.2 Stage data

Stage data are required at all external boundaries of the modeled system in order to specify boundary conditions. (Stage typically is required even if discharge is used as the upstream boundary condition because stage is generally needed in the computation of discharge, whether from a stage-discharge relation or *in situ* velocity meters.) Multiple channel systems require stage data at upstream and downstream external boundaries of each channel. Stage data are not required at internal junctions, where channels join within the model domain. Stage also should be measured in at least one, and preferably three, locations within the model domain to provide data for model calibration and testing.

It is critically important that all stage measurements be referenced to a common datum. Errors in gage datum translate into errors in water-surface slope, which greatly affects computed streamflow through the third term in equation 2. Correct datums are particularly important (and perhaps more difficult to obtain) for low-gradient channels, where unsteady flow models are often applied. The use of discharge as the upstream boundary condition removes much of the uncertainty associated with potential errors in gage datums.

Except in very large rivers (widths of several hundred meters or more), stage should be measured at 15-minute intervals or less for reliable modeling of flow transients. If possible, the stage measurement interval should be a whole multiple of the computational interval, and should be no more than about five times the computational interval.

Synchronous measurement of stage at all recorders also is required for application of unsteady flow models for computing streamflow. Asynchronous measurements, like datum errors, translate into errors in water-surface slope and, hence, errors in computed streamflow.

Stage should be measured following procedures outlined in ISO 1100-1 using equipment described in ISO 4373.

6.3 Velocity data

Measurements of velocity in the study reach are required to (1) evaluate the assumption of one-dimensional flow and (2) compute the momentum coefficient (equation 3). Stream velocities obtained during discharge measurements generally are adequate for these purposes.

Velocities should be measured following procedures outlined in ISO 748 or ISO 2425 using equipment described in ISO 2537 and ISO 3454.

6.4 Discharge data

Discharge data are required for model calibration, and may be needed as boundary data. Discharge data may be either (1) a continuous time series obtained from a stage-discharge rating or by using the *in situ* velocity meters, such as ultrasonic velocity meters) or (2) discrete measurements. Time-series of discharge are generally required only at the upstream boundaries. Discrete measurements are made within the model domain for the purposes of model calibration and testing.

Discharge should be measured using methods described in ISO 748, ISO 1070, ISO 1100-1 and 1100-2, ISO 2425, ISO 6416 and ISO 9555, all Parts.

6.5 Lateral inflows and withdrawals

Time-varying records of major inflows into and withdrawals from the modeled reach must be included in the model to maintain mass balance. Inflows or losses which are relatively constant throughout the modeled reach, such as ground-water inputs or losses, can be lumped into a few discrete points in the reach or can be included at each computational node. Inflows from major streams must be gaged. Inflows from minor streams and local areas along the channel can be estimated using data from nearby gaged streams and drainage area ratios.

6.6 Channel cross section data

Cross-sectional data consists of a set of longitudinal, lateral, and vertical coordinates which describe the location and configuration of the cross section. A measured cross section is typically required at each computational node within the model. The exact spacing of the computational nodes, however, is not known until convergence testing has been completed and stability criteria have been evaluated.

Numerical solutions of the governing equations generally use the average of the measured cross sections at the upstream and downstream ends of a reach to represent the cross-sectional geometry of the entire reach bounded by the two measured sections. Consequently, measured cross sections should be fairly representative of conditions upstream and downstream of the measurement. The measured sections also should be spaced sufficiently close so that large changes in channel geometry do not occur between the sections.

The longitudinal distance between cross sections can be determined from a map having a scale of 1:24,000 or larger. Longitudinal distances should be measured along the centerline of the channel.

Cross sections should be measured in accordance with ISO 748 or by using a recording fathometer. It is generally not practical to run levels from an established benchmark to each cross section. Consequently, cross sections can be measured during steady flow, when water levels are not changing, and the stage at the measurement site can be interpolated from measured stage at upstream and downstream stage recorders. Cross sections must be referenced to the same datum as the stage records.

7 CALIBRATION AND TESTING OF UNSTEADY FLOW MODELS

Modeling is based on abstraction of a physical system to a mathematical expression and replication of the system using theses expressions and appropriate field data. The analyst must identify the important features of the flow system and ensure that those features are reflected in the model which is selected for application to the study reach. Important general model attributes include (1) the ability to simulate a wide range of flow conditions; (2) the ability to represent a range of complex channel conditions and geometries; (3) a stable, numerically-convergent, efficient computational scheme, and (4) a system for processing model input data and output simulation results.

7.1 Preliminary tests

In many cases, it is appropriate to conduct preliminary tests using simplified channel geometry and boundary conditions with the unsteady flow model. Tests should be conducted if the model is poorly documented, or if the user is unfamiliar with the model.

Tests should be conducted using a channel which has a uniform, rectangular cross section, and with the model configured for the study reach. Tests using the rectangular cross-section model could include the following:
- No inflow and no bed slope--no flow should be generated within the model domain.
- Steady inflow--mass should be conserved.
- Unsteady inflow--mass should be conserved.
- Triangular-shaped inflow hydrograph in channel with no bed slope--peak flow should not be significantly attenuated.

After the model for the study reach has been constructed using the measured cross-sectional data, tests which should be performed include:
- No inflow or water surface slope--no flow should be generated in the model domain; this test also determines if unintentional openings in the boundaries are present.
- Steady and unsteady flow--mass should be conserved.
- Rapid change in inflow boundary conditions--no numerical instabilities should be generated.
- Change in boundary conditions from one steady flow to another flow--the amount of time required for all flows within the model domain to reach the new steady-state condition is an indication of how long initial conditions persist within the model domain; model results generally are not accepted until effects of the initial conditions are transported out of the model domain so that model is responding to boundary conditions only.

Other tests may be performed as needed, but these simple tests can be used to document general model performance and should allow users to gain a better understanding of model capabilities and limitations prior to application to the study reach.

7.2 Computational grid and time step

The computational grid is used to represent the physical system in the unsteady flow model. Junctions, inflows, and outflows must be represented by the computational grid.

The channel system is subdivided into a number of finite segments for solution of the numerical approximation of the governing equations. The solution points are either at the ends or the midpoint of each segment. The computational grid should be established such that computations of stage and discharge coincide with locations of data collection, or at locations where computed data are required. Measured cross-sectional data should be available at the ends of each computational segment or grid cell.

Some models allow nonuniform segment lengths, but others require that all segments have the same length. Segment lengths should be at least three times greater than the width of the channel, and are frequently five to ten times the channel width. Exact segment length is determined during convergence testing.

The representation of overbank areas, or the flood plain, in the model must be done with caution. For relatively narrow flood plains in which the flow length of the flood plain is very nearly equal to the flow length of the channel, model assumptions of one-dimensional flow are not violated. Broad flood plains, which bound a sinuous channel, may have distinctly different flow lengths than does the channel. Moreover, filling and draining of the flood plain may lag the rise and fall of water in the channel. In these cases, the one-dimensional flow model described in this standard is not appropriate for application.

In some instances, off-channel storage reservoirs have been included in one-dimensional flow models to account for storage and release of water from the flood plain. These formulations account for the slow storage and release of flood plain waters. However, such a model design also converts a process which occurs throughout some finite reach of the channel into a single point process.

The computational time step should be sufficiently small to accurately represent flow transients which occur in the modeled system. Generally, the computational time step is reduced to meet stability criteria rather than adjusting the spatial discretization interval. As with the computational grid, convergence testing helps define the maximum time step which can be used.

7.3 Convergence testing

A finite-difference solution to a partial-differential equation is spatially convergent if the numerical solution approaches the true solution of the differential equation as the finite-difference spatial discretization approaches zero. Spatial convergency can be tested by repeatedly applying the model with a fixed set of boundary conditions for successively smaller computational discretizations. The model is spatially convergent if no further change in model results is observed as the spatial step is refined. Likewise, a model is temporally convergent if model results remain substantially unchanged as the computational time step is decreased. To determine the effects of

spatial discretization and time step on model results, convergence testing should be conducted prior to model calibration.

7.4 Boundary and initial conditions

Two initial conditions (Q and z for the formulation of the unsteady flow equations used in this standard) are required at each computational node in the model domain. For the initial application of the model to a study reach, common initial conditions are a steady flow, equal to the initial boundary-condition flow, and a water surface which slopes linearly from a measured upstream stage to a measured downstream stage. Output from a previous unsteady flow model application also may be used to determine initial conditions for a simulation which follows sequentially in time.

The model may only be applied for periods which have measured boundary conditions. Boundary conditions include a time series of measured stage at the downstream boundaries, measured stage or discharge at the upstream boundaries, and measured lateral inflows. As previously discussed, better results often are obtained when discharge is used as the upstream boundary condition.

7.5 Calibration

Model calibration is required to adapt a general unsteady flow model to the specific application for which streamflows are to be computed. Calibrations is accomplished by adjusting model parameters until model results agree with observations. Essentially all components of the model are subject to adjustment during model calibration. Components that are directly measurable and physically well defined, however, are typically less subject to adjustment than are those that might not be directly measured. Measures for quantifying the calibration are discussed in Section 7.6.

Initially, the resistance coefficient, momentum coefficient, and weighting coefficients for the numerical scheme should be varied, because these parameters cannot be measured. Boundary gage datums may be adjusted slightly if there is some uncertainty about the accuracy of the datum. Cross-sectional geometry also may be adjusted during the calibration process. Adjustment of channel geometry is justified because the measured cross sections are used to represent the average conditions within a computational segment, rather than the actual conditions at the measured cross section.

It is entirely possible to achieve a well-calibrated model with empirical coefficients which bear little resemblance to those justified by the physics and setting of the study reach. In such a case, application of the model to another conditions is not justified without another calibration.

Because of the important assumptions of the governing equations is that the channel is stable, and most natural channels undergo continuous change, model calibrations should be repeated at least annually. The amount of data required for the subsequent model calibrations should not be as great as for the initial calibration, unless the user suspects dramatic changes in the stream geometry.

7.6 Validation

Validation refers to comparison of model results to measured stage and discharge. Calibration data should not be used for validation.

Graphical comparisons of measured and simulated information are often used, but may be misleading. Quantitative measures of validation include measures of deviation and testing of the statistical significance of the deviation. Measures of deviation between model results and data include absolute and relative error, and root mean square deviations.

Statistical tests of significance are necessary to determine whether deviations are meaningful or whether they are simply related to variability in data. However, statistically independent data are needed to test for significance. Consequently, data and model results must be sampled at intervals greater than the correlation time scale before applying certain statistical tests, such as the t-test.

If possible, the model should be validated over the range of flow conditions for which the model is to be applied. The model may be applied to flows reasonably outside the range for which the model was tested, as long as conditions do not change appreciably. For example, a model calibrated for flows less than bankfull should not be applied to simulate overbank flows.

Greater emphasis should be placed in validating against discharge rather than stage, because the purpose of the model is to compute streamflow. However, in most case, stage data are much easier and less expensive to obtain than are discharge data, and more stage data will be available for use in calibration, validation, and testing.

7.7 Sensitivity testing

Sensitivity testing consists of evaluating the sensitivity of model results to changes in selected model parameters. Parameters, or conditions, which should be included in the sensitivity testing include the resistance coefficient, the weighting coefficients used in the numerical scheme, the momentum coefficient, boundary gage datums (particularly if stage is used as the upstream boundary condition), and channel geometry. The usual procedure is to successively increment the parameters by small amounts, apply the model, and compare the results with results from the calibrated model. A model which is highly sensitive to small changes in one or more parameters may become unstable for conditions outside those used for model calibration, and greater care must be taken when applying such a model.

8 UNCERTAINTIES

8.1 Governing equations

Equations 1 and 2 strictly apply to an infinitesimally small volume at an instant in time. For the development and application of unsteady flow models, the equations are assumed to apply to some finite volume, which may have a length on the order of hundreds of meters, a width of tens of