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Simulation of Flood Event in a Reach of the Nile River Using CCHE2D Model

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Abstract

The impact of design flood in terms of water surface level and maximum velocity in a reach on the Nile River is studied, using a depth-averaged two-dimensional model. The reach includes a proposed site for a shipyard maintenance harbour. The CCHE2D model, a depth-averaged two-dimensional model, is selected to perform both the steady state computation, for calibration purposes, and flood routing through the reach to obtain maximum water surface level and velocity information. Manning's coefficient was obtained by matching the computed and measured water surface level in the reach under steady flow conditions. The computed results of velocity and water surface profiles agreed satisfactorily with the measured data. The verified model was then used to simulate a flood event within the same reach. Stage-discharge relationships for various sections within the reach were obtained. The peak water surface level at each section was compared with the flow stage under normal flow conditions. The peak stage was found to be well below the proposed elevation of the construction site. The estimation of the peak velocity and water surface level might be useful for bank protection work.

Key words: river flow simulation, flood stage, stage-discharge relationship

Notation

f_{cor} – Coriolis parameter,
g – gravitational acceleration,
h – depth of flow,
t – time,
u – velocity component in direction x,
v – velocity component in direction y,
x – coordinate direction,

y – coordinate direction,
ρ – density per unit volume,
η – water surface elevation,
τ_{bx} – bed shear stress in direction x,
τ_{by} – bed shear stress in direction y,
τ_{xx} – turbulent normal stress in direction x,
τ_{yy} – turbulent normal stress in direction y,
τ_{xy} – turbulent shear stress,
τ_{yx} – turbulent shear stress,
ν_t – turbulent eddy viscosity.

1. Introduction

The construction of certain riverine structures demand knowledge of flow velocity and water surface level under both normal and extreme flood conditions. The flow velocity and water surface level under normal conditions are either available already or can be measured easily. However, the same data under extreme flow conditions is usually not available. Computational models provide a useful tool to predict the flow velocity and water surface level under design flood conditions. Ideally, the model must be verified using the normal flow condition before it can be applied reliably to predict flow properties under extreme flood conditions.

In this study, the impact of a high flood event in terms of flow velocity and water surface level on a selected reach of the Nile River is investigated. The selected reach contains a proposed site for a shipyard maintenance harbour. The aim of the study is to verify the integrity of the proposed site under high flood and to provide information regarding peak stage and flow velocity that may be useful for designing bank protection work within the reach. The CCHE2D model is adopted to estimate the flow velocity and water surface level within the selected reach during a flood.

Before the model could be applied to estimate flow conditions during a flood, it must be verified. The measured data of the water surface levels and velocity profiles within the reach under normal flow was used to verify the model. The Manning's coefficient for the reach was estimated using normal flow conditions. The computed results of water surface levels and velocity profiles were compared with the measured profiles within the reach. Finally, the calibrated model was used to predict the peak velocity and water surface level and stage discharge relationship at selected sections within the reach.

2. Model Description

The CCHE2D model, developed at the National Center for Computational Hydroscience and Engineering, The University of Mississippi, is a two-dimensional depth-averaged, unsteady, turbulent flow model with uniform and non-uniform sediment transport capabilities. The model is capable of handling wetting and drying during simulation through a critical depth criteria specified by the user. If the depth at a node falls below the critical depth, the node is considered dry. The model provides three different turbulent closure schemes. These include depth-averaged parabolic eddy viscosity model, mixing length model, and depth-averaged $\kappa - \varepsilon$ model. The last two turbulent closure schemes are particularly useful when accurate prediction of reverse flow is necessary or detailed flow pattern near a hydraulics structure is desired. The model allows for total slip condition, no slip, or log-law boundary condition at no flow boundaries to accurately predict variety of flow situations.

2.1. Governing Equations

The two dimensional, depth-averaged mass and momentum conservation equations used in the CCHE2D model are given below.

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \eta}{\partial x} = \frac{1}{\rho h}\frac{\partial h\tau_{xx}}{\partial x} + \frac{1}{\rho h}\frac{\partial h\tau_{xy}}{\partial x} - \frac{\tau_{bx}}{\rho h} + f_{cor}\, v, \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \eta}{\partial y} = \frac{1}{\rho h}\frac{\partial h\tau_{yx}}{\partial x} + \frac{1}{\rho h}\frac{\partial h\tau_{yy}}{\partial x} - \frac{\tau_{by}}{\rho h} + f_{cor} u. \tag{3}$$

In the above equations h is the depth of flow, u and v are velocity components in the x and y directions, x and y are spatial coordinates, t represents time, g is gravitational acceleration, η is the water surface elevation, and ρ is the density of water. The normal turbulent stresses in the x and y directions are represented by τ_{xx} and τ_{yy}, τ_{xy} and τ_{yx} are shear stresses, τ_{bx} and τ_{by} are bed shear stresses in the x and y directions, and f_{cor} is a Coriolis parameter.

Boussinesq's assumption is used to approximate the turbulent normal and shear stresses as follows

$$\tau_{xx} = 2\rho\nu_t\frac{\partial u}{\partial x}, \tag{4}$$

$$\tau_{xy} = \tau_{yx} = \rho\nu_t\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right), \tag{5}$$

$$\tau_{yy} = 2\rho\nu_t\frac{\partial v}{\partial y}, \tag{6}$$

where ν_t is turbulent eddy viscosity. The turbulent eddy viscosity is approximated using three different methods. The first method is based on the depth-averaged parabolic eddy viscosity model, the second method uses depth-averaged mixing length model, and the last method is based on depth-averaged $\kappa - \varepsilon$ model.

2.2. Numerical Scheme

The CCHE2D model employs the efficient element, implicit, numerical scheme to solve the momentum equations. The scheme requires a quadrilateral structured mesh system. A working element is formed around each node. The working element consists of a central node (the node at which the variables are calculated) and eight surrounding nodes. Quadratic interpolation functions are used to approximate the variables and its derivatives. For details of the scheme, the readers are referred to Wang and Hu (1992). The continuity equation is solved for water surface elevation by drawing a control volume around the central node of each element and the control volume approach is used to approximate the mass fluxes entering and leaving the control volume. The control volume method guarantees mass conservation.

2.3. Boundary Conditions

The CCHE2D model identifies three different types of boundary conditions in the computational domain: a solid wall boundary, an inlet boundary, and an outlet boundary. At a wall boundary, the normal component of the velocity is set at zero. The user can set the tangential component of the velocity to zero (no-slip condition) or to total slip at the wall. The model also allows for the application of a log-law at a solid boundary. The log-law approach foresees a partial slip at the wall in order to predict accurately the shear stress at the wall. For application of a log-law or no-slip boundary condition, the mesh near the wall should be relatively fine to reasonably identify the boundary layer profile. For most natural-river applications, a total-slip condition suffices.

At an inlet boundary, three different boundary conditions can be specified: the specific discharge, the total discharge, and the discharge hydrograph. One of the following four boundary conditions can be applied at an outlet: the stage, the stage as a function of time, the stage-discharge relationship, and open boundary condition or a kinematic wave condition. The last boundary condition is useful when the stage at the outlet cannot be ascertained.

3. Simulation Domain

A shipyard maintenance harbour construction is planned at an elevation of 78.0 m between kilometers 733.0 and 727.8 (measured from Elroda) on the West bank of the River Nile. The reach is located downstream of the Aswan Dam and the flow is well regulated. The 5.2 km river reach had been extensively surveyed by the Nile Research Institute in 1998. In addition, the velocity and water surface elevation were measured in detail within this reach under normal flow conditions. It was essential to investigate flow velocity and water surface level under flood conditions to verify the safety of the proposed shipyard site. The flow velocity and water surface elevation under flood conditions may also provide necessary information for bank protection work within the same reach.

The topographic survey was confined to the waterline under normal flow conditions. However, to simulate flood flows within the reach, the floodplains data was needed. The necessary data was obtained from historical maps and added to the survey data. The resulting computational domain is shown in Fig. 1. The figure also shows the proposed construction site for the shipyard. The cross-sections at which velocity and water surface level were measured are also shown in the figure. A structured mesh with quadrilaterals was generated for the river reach. Special attention was paid to match the measured topography of the cross-sections labelled in the figure with that generated by the mesh generator.

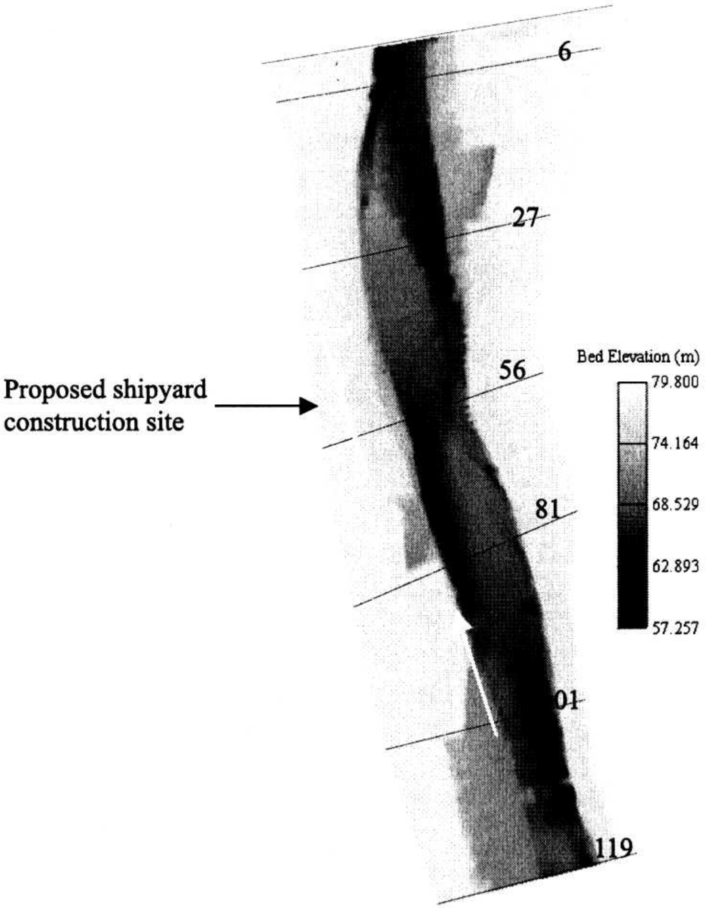


Fig. 1. Simulated reach of the Nile River

4. Model Calibration

The CCHE2D model was calibrated using measured data of water surface level and velocity profiles under steady flow condition. A discharge of 1330 m^3/s was used as a boundary condition at the upstream end of the channel and a water surface level of 70.83 m was used as downstream boundary condition. The values of discharge and water surface level were obtained from the records at El Hanadi station during the measuring period. Manning's coefficient of 0.022 $m^{-1/3}s$ for the main channel was found to provide the best fit between the computed and measured water surface levels at all six cross-sections. Although the floodplains were not inundated, both the main channel and the floodplains were included in generating the mesh for the river reach shown in Fig. 1. The nodes in the longitudinal and transverse directions were 119 and 90 respectively. A Mannings coefficient of 0.07 $m^{-1/3}s$, assessed based on the vegetation cover, was used for both the west and east floodplains. The depth-averaged parabolic eddy viscosity was selected for approximating turbulent viscosity and total slip boundary condition was used at the no-flow boundaries.

The water surface level profiles are shown in Fig. 2 (a-f). The computed water surface profiles conform quite well with the measured data at all six cross-sections. Fig. 3 (a-f) shows a comparison between computed and measured velocity profiles for the six cross-sections. The computed velocity profiles, except for cross-section 101, show satisfactory agreement with the measured velocity profiles. The computed results of water surface level and velocity profiles show that the CCHE2D model can be used to predict the stage and velocity for the flood conditions.

5. Flood Wave Simulation

Flood hydrograph data for the Nile Rive was not available for the boundary condition. The Aswan High Dam regulates not only the normal discharge but also the floodwater. It can either store the floodwater or allow it to pass through by adjusting the discharge through the dam. Since the Aswan High Dam controls fully the flow in the downstream river, it was decided to use the peak discharge that could be released from the Aswan High Dam and use the function proposed by Ponce and Theurer (1982) to generate a flood hydrograph. The equations used to obtain the discharge hydrograph are provided below.

$$Q(t) = Q_{base} \quad \text{for} \quad t \le t_{base}, \tag{7a}$$

$$Q(t) = \left(Q_{peak} - Q_{base}\right) t_h^m e^{(m(1-t_h))} + Q_{base} \quad \text{for} \quad t > t_{base}, \tag{7b}$$

$$t_h = \frac{t - t_{start}}{t - t_{peak}}. \tag{7c}$$

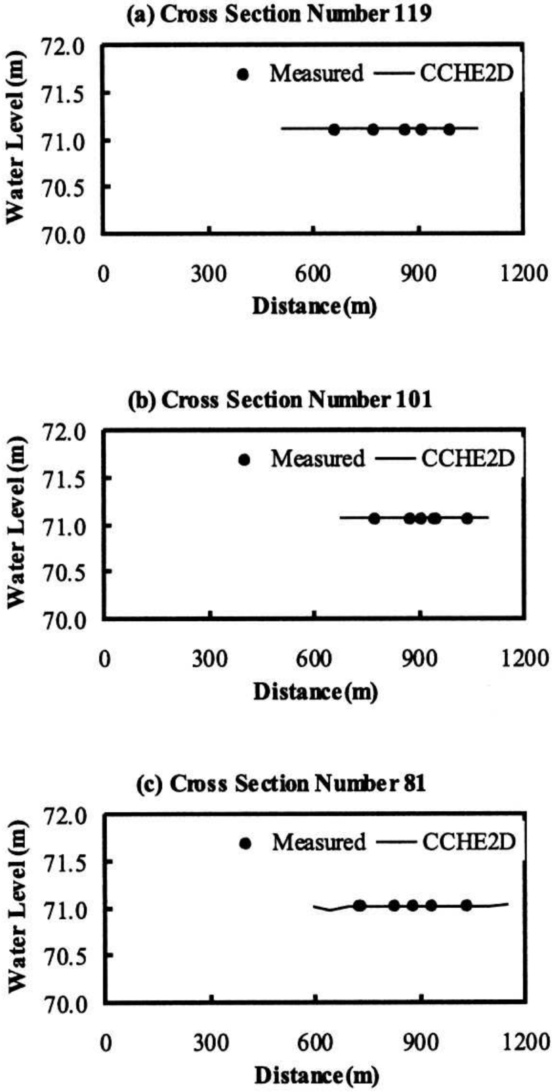
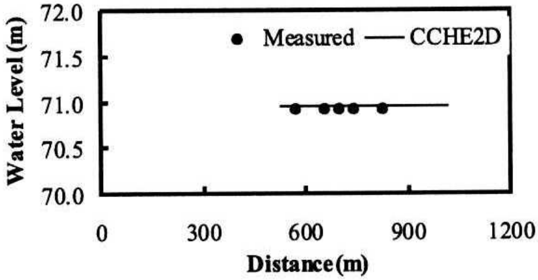
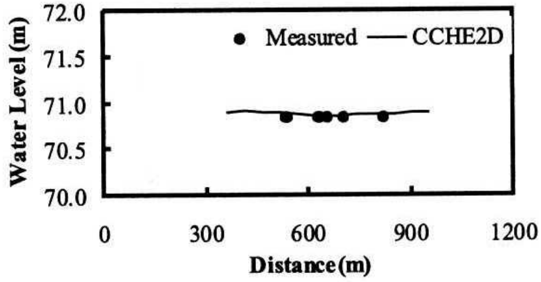


Fig. 2. a-c. Comparison of computed and measured water surface levels

In the above equations Q_{base} and Q_{peak} are respectively base and peak discharges, t is time and m is a parameter to control the shape of the hydrograph. A base discharge of 1330 m^3/s and peak discharge of 4000 m^3/s were used to generate the discharge hydrograph. The peak discharge value is the maximum discharge that could be released from the Aswan High Dam. The t_{peak} and m values were set at 1800 sec and 1.5, respectively. The generated discharge hydrograph was used as a boundary condition at the upstream end. Since the downstream boundary con-


(d) Cross Section Number 56


(e) Cross Section Number 27

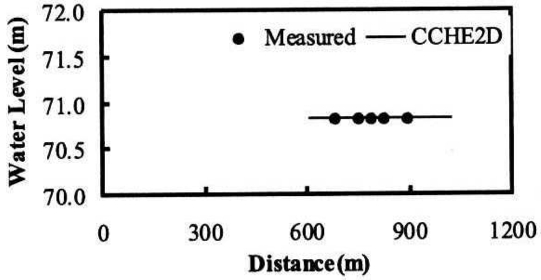

(f) Cross Section Number 6

Fig. 2. d–f. Comparison of computed and measured water surface levels

dition could not be ascertained, the river reach was extended downstream and a uniform flow boundary condition was applied at the extended downstream boundary. The extended length of the reach was such that the leading edge of the flood wave did not reach the downstream end during simulation. Manning's *n* value for the flood plains and main channel were as described above. The turbulent eddy

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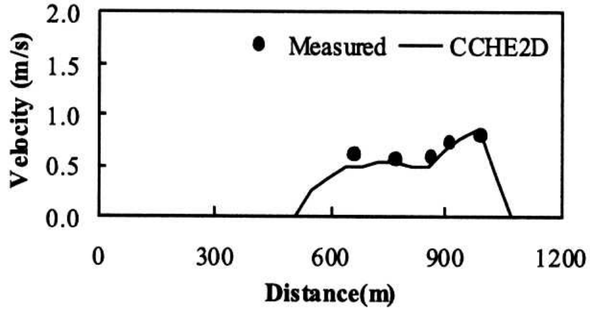
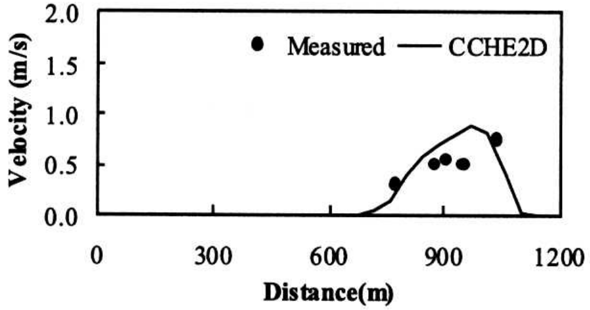


(b) Cross Section Number 101



(c) Cross Section Number 81

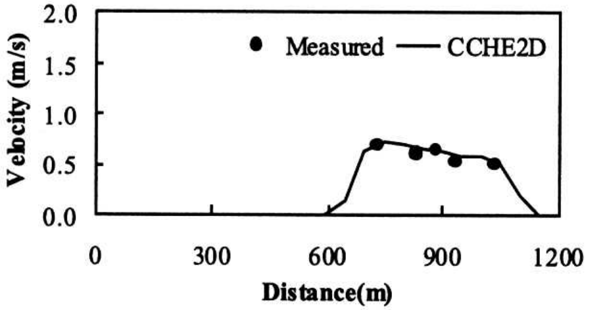
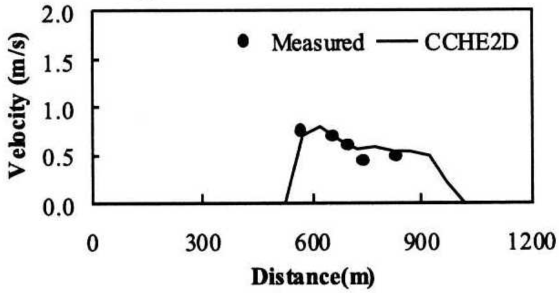


Fig. 3. a–c. Comparison of computed and measured velocity profiles

viscosity was calculated using the depth-averaged parabolic eddy viscosity scheme and total slip boundary condition was used at no-flow boundaries.

Fig. 4 shows the generated inlet hydrograph. The peak of the hydrograph occurs at 0.5 hour and the total duration is three hours. Fig. 5 shows the stage-discharge plot for the selected sections in the reach. The peak discharge and the peak stage reduce as the flood hydrograph moves downstream. A comparison of the steady state and the peak water surface levels during the flood is shown in Fig. 6 (a-d). The results show that floodwater will climb up to the first

(d) Cross Section Number 56



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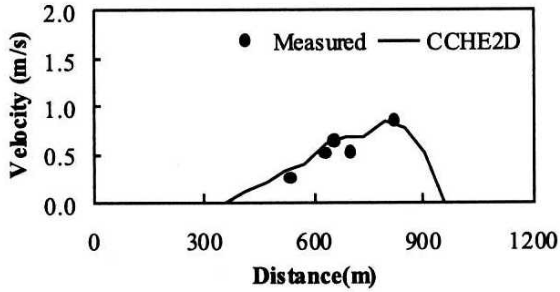

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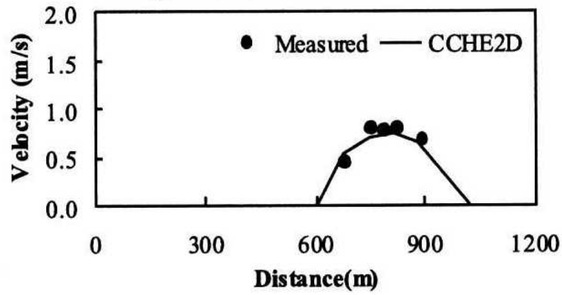


Fig. 3. d–f. Comparison of computed and measured velocity profiles

flood terrace but will not reach the maximum level elevation. In fact, the peak water surface level is below the 78.0 m mark at all cross-sections for the flood situation considered in the study and hence will not reach the proposed shipyard site.

6. Summary and Conclusions

The impact of a flood event on a selected Nile River reach was studied. The main aim of the study was to investigate the integrity of a proposed shipyard site

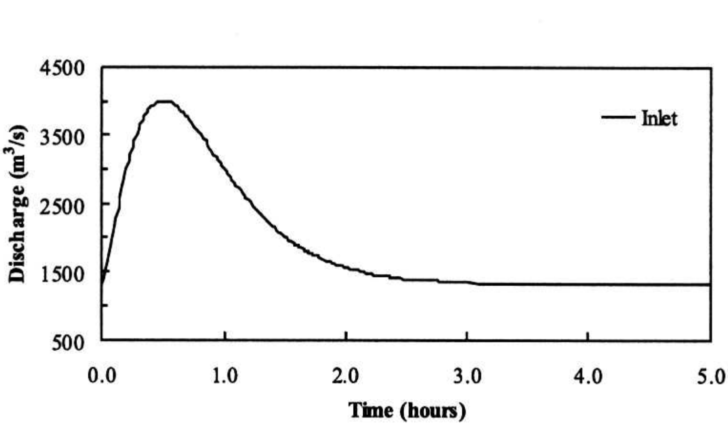


Fig. 4. Inlet flow hydrograph

under a flood event using the CCHE2D model. The topography of the reach was extensively studied. In addition, water surface and velocity profiles were measured under normal flow conditions at selected sections. The CCHE2D model was validated using the measured water surface and velocity profiles. Uniform Manning's *n* value for the main channel in the studied river reach was adopted. The value was determined through iterative process. The adopted value minimized the difference between the computed and measured water surface level.

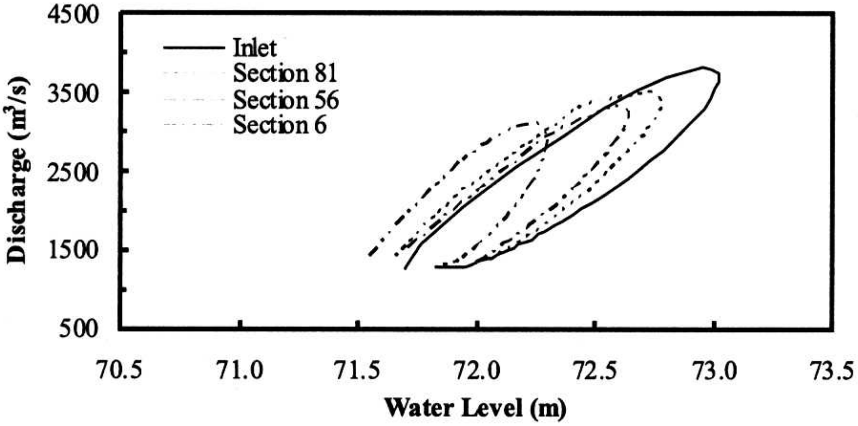
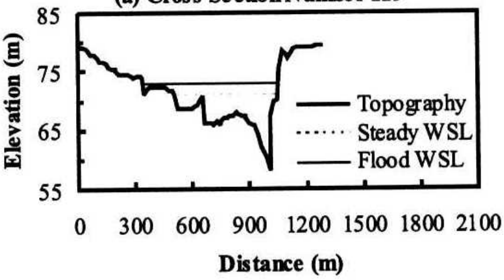
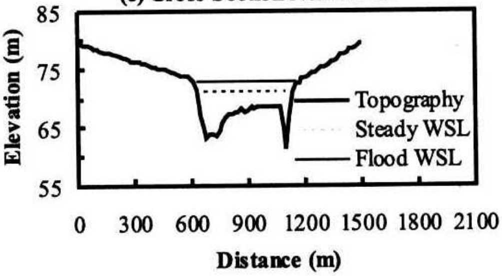


Fig. 5. Stage-discharge relationship at selected stations

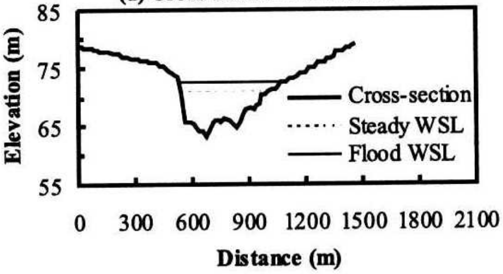
To simulate a flood event through the studied reach, floodplains were added to the main channel. The peak discharge from the Aswan High Dam was used to generate a hypothetical flood hydrograph. The calibrated model was used



(a) Cross Section Number 119



(c) Cross Section Number 81



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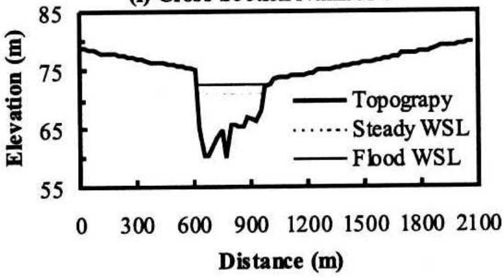

(f) Cross Section Number 6

Fig. 6. Comparison of normal and peak water levels

to simulate the flood event through the reach. The stage-discharge hydrograph relationship was computed for the selected sections in the reach. In addition, comparison between the normal flow stage and the maximum stage during the flood was made. The peak stage during the flood was well below the proposed construction elevation of 78.0 m at all the sections within the reach. The peak velocity and water surface elevation data computed under flood conditions within the reach would be invaluable for bank protection work.

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