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A numerical model of general scour at channel constrictions

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ABSTRACT

Scour is a major cause of bridge failure. Bridge scour may be due to the local effect of flow disturbance at piers or abutments, or may be caused by a constriction in the flow area, for example due to bridge abutments. Current methods for estimating scour at a constriction do not take into account many factors which are thought to be important. This study has examined the use of a numerical flow and sediment transport model to predict scour at constrictions. Scour in an idealised river channel has been simulated in order to examine the effect of different degrees of constriction, discharges, sediment sizes and flood durations. Results have been compared with predictions given by existing formulae.

It has been shown that the numerical model can represent, at least qualitatively, the process of general scour. Recommendations are given for further work to develop the method and to verify that the method can be used to produce reliable quantitative predictions. These are needed to improve estimates of general scour at constrictions at both new and existing structures, and could lead to the formulation of design guidelines.

NOTATION

A	Cross-sectional area of flow
a	Ackers-White parameter
B	channel width
C	silt concentration by mass
c	Ackers-White parameter
D	sediment diameter
D_{gr}	dimensionless grain size
d	depth of flow
F_{gr}	Ackers-White sediment mobility
G	sediment transport rate
G_{gr}	dimensionless sand transport rate
g	acceleration due to gravity
m	Ackers-White parameter
n	Ackers-White parameter
Q	discharge
s	specific gravity of sand
S_y	bed slope
S_f	friction slope
t	time
v_*	shear velocity
X	sand concentration by mass
x	distance along channel
z	bed height
ν	kinematic viscosity of fluid
v	flow velocity

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1. INTRODUCTION

In natural channels in which the bed of a river can be moved by the flow, the bed level may fluctuate up and down as the flow varies. Any reduction in bed level is generally referred to as scour, or erosion. Scour is an important factor in the safety or stability of any structure associated with the river, such as a bridge. If the bed level of the river around a bridge is lowered then the loss of foundation strength or, in the extreme case, the undermining of the foundations, may lead to the failure of the structure. Regrettably, failure due to scour is not uncommon. Smith (1976), in a study of bridge failures, showed that 59% of failures of bridges over 2 years old were due to bridge hydraulics. The vast majority of these failures were attributed to scour.

To design a new structure or to assess the safety of an existing one it is important to be able to predict how much scour can take place. This report describes experiments which examine the use of a numerical model to predict scour due to the constriction of a river channel.

In order to predict the total depth of scour at a bridge, it is necessary firstly to identify the different types of scour, which are caused by distinct processes. Four types of scour can be identified; local scour, general scour, natural scour and progressive degradation. Local scour is a lowering of the bed level adjacent to structures such as piers and abutments, and is caused by complex three-dimensional flows around obstructions. General scour results from the increase in flow velocities at a constriction. The constriction may for example be due to a narrowing of the river between bridge abutments. General scour can occur across the whole width of the river, whereas local scour is confined to the region adjacent to the obstruction. Both types are confined to the reach of river in the neighbourhood of the bridge. Figure 1 shows local and general scour at a typical bridge.

Natural scour and progressive degradation are not confined to the neighbourhood of structures, but can occur over long reaches of river. This type of bed level change is associated with natural or man made changes to the river regime, and may be independent of the structures which are affected.

This report describes a study in which a numerical model has been used to simulate general scour at a river constriction.

2. PREDICTION OF LOCAL AND GENERAL SCOUR

Various method are available for predicting scour. In general, different methods are used to study different types of scour. As a first approximation, the total scour at a bridge is often assumed to be the sum of the different types of scour acting at the bridge. In order to assess the scour at a particular bridge site, it is therefore necessary to be able to predict scour due to the different causes outlined above.
Local scour has been examined by many workers using scale models in the laboratory. Numerous formulae are available to predict local scour at full sized structures based on these physical model tests. Local scour is essentially a very complex three-dimensional phenomenon, and numerical methods have as yet made little impact on prediction methods available to engineers.

At present the only methods available to predict general scour are either empirical or based on regime theory. Regime theory is concerned with predictions of the size and shape of alluvial channels. In regime theory it is appreciated that the behaviour of the system involves many fluctuating factors but regime theory aims to predict average values. In predicting general scour, however, one has to predict the magnitude of the fluctuations about the mean. Regime and empirical methods should strictly only be applied to conditions similar to those on which the formulae were originally founded. In general, these methods were developed in order to explain dimensions of stable channels, and are used in canal design. General scour at a bridge is a distinctly different problem, and may lie outside the range of applicability of the existing methods. The engineer may be basing bridge design or risk analysis on a poor estimate of scour.

General scour is caused by variations in conditions along the length of the river and therefore predictions of general scour must take into account the variations in the river immediately upstream and downstream of the bridge. Furthermore, scour is time-dependant, and even under steady discharge conditions, scour takes time to develop depending on the sediment transport conditions in the river. Methods for predicting general scour do not take this into account, and may therefore lead to poor estimates of scour. Current methods cannot take account of non-steady flows during flood events.

A fundamental weakness of the available methods for general scour is that they do not attempt to represent the physical reality of scour. This report describes a study to examine the feasibility of applying a numerical sediment transport model to predict general scour. The model is based on physical principles rather than empirical or regime methods, and is therefore expected to provide better predictions and to be applicable over a wider range of circumstances.

3. MORPHOLOGICAL RIVER MODELS

Morphological river models are used to predict changes in bed level by determining the variation in sediment transport along a river. The technique is used to study overall changes in bed level that take place over long lengths of river over a large number of years, such as degradation downstream of a dam. General scour is caused by variations in sediment transport rate along a river, but the changes take place over a short length of river, during the duration of a flood. The length and time scales for general scour are therefore different to those of river morphology problems. General scour occurs over a shorter time and shorter length of river than river morphology problems. This study aimed to determine whether morphological models can be used to represent general scour.

The model used for was closely based on the morphological river model MORPH.

MORPH has been used in numerous studies to predict the long term changes to bed and water levels resulting from engineering works.

3.1 Numerical Model MORPH

3.1.1 Model formulation

The numerical model is based upon the equations which describe the flow and sediment movement in open channels. It is a time-stepping model, that is, given initial conditions along the length of the channel the equations are used to predict what happens in the channel over a short time period Δt, so that conditons are determined at the end of that time-step. A repetition of the procedure predicts the conditions after a time $2\Delta t$. The process is then repeated a sufficient number of times to make predictions for the required time period.

The model is one-dimensional, that is, only variations along the length of the channel are considered and all the quantities calculated are averaged over the cross sectional area. No account can be taken of variations across the width or through the depth. The model is only suitable for simulating gereral erosion or deposition, and cannot be used to examine local effects such as local scour, or bank erosion.

3.1.2 Equations of water flow

The model is based upon the St Venant equations which describe the slowly varying unsteady flow of water in an open channel. The equations consist of a continuity equation which implies that the volume of water is conserved throughout the system,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

and a dynamic equation, in which the forces involved are related to the product of mass and acceleration,

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\,\frac{\partial d}{\partial x} = gA\,(S_y - S_f)$$

The equations determine the water discharge and depth as a function of distance and time.

An assumption is made that changes in the water flow take place on a much shorter time scale than those of the bed level, the flow can therefore be regarded as steady. The calculation of the water flow, therefore, reduces to a simple steady flow or backwater calculation. Given a downstream discharge and a rating curve, that is, a relationship between discharge and water level, the method used essentially follows that given by Chow (1959) with a Newton-Raphson iteration to determine the unknown upstream water level. The water level, velocity and water-surface slope are then determined at the locations of cross sections.

3.1.3.1 Sediment transport equations

The transport of sediment at each cross-section is calculated using the Ackers and White (1973) sediment transport theory. In tests on an extensive set of field and flume data this theory produced the most satisfactory predictions of sediment transport (White, Milli and Crabbe, 1975).

The Ackers-White equations centre on several non dimensional quantities; each have a distinct significance but incorporate coefficients determined from empirical data.

The sediment mobility F_{gr} is defined to be:

$$F_{gr} = \frac{v_*^n}{(gD(s-1))} \left[\frac{v}{(32)^{0.5} \log (10d/D)}\right]^{(1-n)}$$

where

n is the Ackers-White transition exponent.

The concentration is given by:

$$X = G_{gr} \frac{sD}{d} \left(\frac{v}{v_*}\right)^n$$

where

$$G_{gr} = c \left(\frac{F_{gr}}{a} - 1\right)^m$$

c = Ackers-White parameter

a = value of F_{gr} at initial motion

m = Ackers-White parameter

n = Ackers-White parameter

The parameters n, a, m and c are functions of the dimensionless particle size D_{gr} defined by:

$$D_{gr} = D \left(\frac{g\ (s-1)}{\nu^2}\right)^{1/3}$$

For coarser sediments ($D_{gr} \geq 60$);

$n = 0.0$

$a = 0.17$

$m = 1.5$

$c = 0.025$

and for transitional sizes ($60 \geq D_{gr} \geq 1$);

$$n = 1.0 - 0.56 \log D_{gr}$$

$$a = \frac{0.23}{(D_{gr})^{1/2}} + 0.14$$

$$m = \frac{9.66}{(D_{gr})} + 1.34$$

$$\log c = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53$$

3.1.3.2 Sediment conservation

Since sediment is neither lost not gained differences between the volume of the sediment passing adjacent cross-sections must lead to the deposition or erosion of sediment on or from the bed. Since the volumes of sediment passing each section are determined the change in bed levels may be calculated. Mathematically this conservation of sediment is described by the equation,

$$B \frac{\partial z}{\partial t} + \frac{\partial G}{\partial x} = 0$$

The numerical solution of this sediment continuity equation is based on a first-order finite-difference approximation. The changes in bed level during the time-step are, therefore, calculated. The bed levels are then updated and the calculation repeated for the next time-step.

4. NUMERICAL MODEL OF GENERAL SCOUR

4.1 Modelling concerns

In view of the fact that the morphological model had not previously been for applied to problems of this type, preliminary work was needed to ensure that the model was representing the process of general scour. The following aspects required particular attention:

a) Selection of space and time steps. The numerical scheme used to solve the sediment continuity equation is known to become unstable if the timestep is too long in relation to the space step and the rate of migration of bed perturbations. Furthermore, a long timestep may reduce the accuracy of the model predictions. Having first selected a suitable space step, experiments were conducted to establish the timestep required to ensure that the model would be both stable and accurate. In order to resolve the process of general scour at the constriction, a uniform space step of 25m was selected. This was selected on the basis of the channel constriction and dimensions. Experiments were carried out with wider space steps in the reaches upstream and downstream of the constriction. This would have enabled the reach to be modelled with less computation time, but it was found that widely varying space steps lead to model instability and physically unreasonable results. It was therefore decided to use uniform space steps throughout the model, and accept that the resolution away from the bridge site would be higher than required.

The timestep required to ensure stability and accuracy was then found to be 60,000 seconds. This gave essentially identical results as a timestep of 6000 seconds. The experiments described in this report were carried out with a timestep of 60,000 seconds, or 16.667 hours.

b) Representation of constriction

It was found that a fairly simple method could be used to effectively represent the constriction. The width of two adjacent sections was reduced to the required constricted width. The constricted sections were located midway along the modelled reach. Gradual transitions in width upstream and downstream of the constriction were not required, although it is expected that more elaborate methods would be required if more severe constrictions were studied. With a section spacing of 25m, and using a backward difference scheme to calculate bed level changes, this is equivalent to a constricted reach with a length of 50m.

c) Boundary conditions

The three boundary conditions required by the model are water and sediment discharge at the upstream cross section, and water level at the downstream cross section. Some care was needed in specifying the correct boundary conditions in order that the model could be used to simulate general scour in the absence of other effects.

The water discharge was specified as required for any individual experiment, and experiments were carried out under both steady and unsteady discharges.

Several options were available for specifying the sediment inflow at the upstream cross section. The method used for the experiments was to base the inflow on calculations using the Ackers and White sediment transport equations. The slope used in these calculations was the energy gradient between the two most upstream sections.

The downstream water depth was calculated from the normal depth of flow in the channel. This is the depth of flow which occurs in a long uniform channel with a given slope, at the required discharge.

The effectiveness of these boundary conditions was tested by using the numerical model to simulate changes in bed and water levels in a straight uniform channel, with no constriction. After simulating a long time period at a high discharge with sediment transport taking place, bed and water levels were unchanged from the initial conditions. We can therefore be confident that predicted bed level changes with a channel constriction in place are due only to the effect of the constriction, and are not caused by the boundary conditions which we have imposed.

4.2 Model experiments

Experiments were carried out to investigate the feasibility of using the morphological river model to predict general scour at a constriction. A set of tests was carried out initially to define numerical and boundary conditions required to enable general scour to be isolated from other sediment transport phenomena which can occur in an open channel. These are discussed in the previous section. Having established a model that appeared to represent general scour, three series of experiments were carried out. These tests examined the effects of channel constriction, discharge and sediment diameter on the development of general scour. These tests were carried out under steady discharge conditions.

In all cases, the channel width was 5m, and the initial bed slope was 0.0002. A total of 77 cross sections at 25m spacing were used to represent the channel of 1900m length. A constriction was modelled by reducing the width of two adjacent sections, 875m and 900m from the upstream model boundary.

The experiments are summarised below:

Series 1: Effect of channel constriction. Three different constrictions were tested. Values of (constriction width/channel width) were 0.9, 0.8, and 0.7. For each of these tests, sediment size and discharge were 0.5mm and $20m^3/s$.

Series 2: Effect of discharge. Three different discharges, 10, 15 and $20m^3/s$ were tested. For each of these tests, the sediment size and channel constriction were 0.5mm and 0.8.

Series 3: Effect of sediment size. Three different sediment sizes were tested: 0.3mm, 0.5mm, and 0.7mm. For each test, the discharge and channel constriction were $20m^3/s$ and 0.8.

In order to illustrate the development of general scour, the experiments in series 1, 2 and 3 were carried out at steady discharges, and no attempt was made to simulate the effect of rising and falling flood, hydrographs. The experiments therefore simulated the effect on an initially unscoured bed of discharge rising rapidly from zero to a steady value.

A further series of tests, Series 4, was designed to investigate the effect of flood hydrographs. A bridge will, in general, be subject to unsteady discharge, and the most severe scour is expected to occur during floods which may have different durations. Two flood hydrographs of different durations but equal flow magnitudes were synthesised, and these were used to investigate the effect on general scour of floods of different durations. The channel constriction was 0.8, and the sediment size was 0.5mm.

Results have been presented graphically. For each experiment in Series 1 to 3, a graph shows the development of the longitudinal profile of bed level with time. The form in all cases is similar. Erosion in the constricted section is initially accompanied by deposition immediately downstream. Erosion tends to a limiting equilibrium value of general scour, and the downstream deposits tend to erode and migrate and diffuse downstream. The bed levels downstream tend to return to the original levels.

Additional figures show how the minimum bed level within the constricted section changes with time, for both steady and unsteady discharge experiments

4.2.1 Effect of constriction

Figures 2 to 5 show the effect of different constrictions on general scour. The constriction is defined as the ratio of the constricted width to the normal channel width. Three constrictions were tested: 0.9, 0.8, and 0.7. Figures 2, 3 and 4 are corresponding longitudinal profiles showing the development of the bed levels with time. Each figure shows the original bed level, and calculated bed levels at 100 hour intervals. In each case, the form of the development of scour is as expected: scour increases with time at the constricted sections, and sediment is deposited downstream of the constriction. This downstream deposit tends to erode and migrate downstream. Bed levels downstream may eventually return to their original values, but the experiments were too short to show this.

General scour resulting from the different constrictions is compared in Figure 5. This shows clearly that for each case, scour develops rapidly at the beginning of the flood, and the rate of scouring decreases with time. Scour eventually tends to reach a limiting value. In each case, the experiments were of sufficient duration for a steady equilibrium to be reached. The final depth of scour for the different constrictions is shown in the table below.

Constriction	Equilibrium depth of scour (m)
0.9	0.51
0.8	1.15
0.7	1.95

4.2.2 Effect of discharge

A series of tests was carried out to investigate the effect of discharge on calculations of general scour using the numerical model.

The sediment size for these tests was 0.5mm, and the channel constriction was 0.8. Figures 6 to 8 show, for each discharge, the development of scour with time. In each case, the pattern of bed level change is as we would expect, with scour in the constricted section accompanied by deposition downstream. Results from the three discharges are compared in Figure 9. In each case, the rate of scour decreases with time, and tends to a steady equilibrium value. This ultimate depth of scour is reached after approximately 300 hours. The highest discharge produces the greatest scour.

The depths of scour due to different discharges are shown below.

Discharge (m^3/s)	Equilibrium depth of scour (m)
10	0.66
15	0.90
20	1.15

4.2.3 Effect of sediment size

The final series of tests was designed to investigate the effect of sediment size on predictions of the development of general scour. Three sediment sizes were tested: 0.7, 0.5, and 0.3mm. The discharge and channel constriction were 20m³/s and 0.8. Development of longitudinal bed profiles are shown in Figures 10 to 12. Figure 13 compares the development of general scour in the constriction. It is observed that sediment size has only a small influence on the ultimate depth of scour, but that the finer sediment is scoured more quickly than the coarser sediment.

The depths of scour due to different sediment sizes are shown below:

Sediment diameter (mm)	Equilibrium depth of scour (m)
0.3	1.26
0.5	1.15
0.7	1.09*

* May not have reached equilibrium depth in duration of test

4.2.4 Effect of flood hydrographs

The tests described so far were carried out under steady discharge conditions. The worst scour at a bridge will occur during a flood, when the discharge generally increases from a relatively low value to a peak value and then falls again to a low value. The duration of the flood hydrograph may affect the depth of scour. The first three series of experiments have shown that scour develops with time, and the maximum scour depth may require a considerable length of time to develop. We would therefore expect that a short flood may cause less scour than a flood of longer duration, even if the peak discharges were the same. Traditional methods of estimating general scour do not take this into account, and only give an estimate of the maximum scour depth. These methods may give conservative estimates of scour, as the flood duration required to produce the ultimate scour depth may be greater than would be expected for the river in question.

Two experiments were carried out to increase understanding of the effect of variable discharge on general scour. In each case, a period of low flow was simulated, followed by the passage of a flood, followed by a period of low flow. For the first experiment, the flood duration was 300 hours, while for the second experiment, the duration was 30.0 hours.

Figure 14 shows the discharge hydrograph and minimum bed level for the longer duration flood. The discharge rises from a steady value of $3.37m^3/s$ to a peak value of $20m^3/s$, before falling again to $3.37m^3/s$. The minimum bed level in the constricted section is shown in this figure. The constriction is subject to general scour during the initial low flow period, when the bed level falls from an initial value of 99.8m to an equilibrium value of 99.52m. During the flood, the bed level falls rapidly due to general scour, and the minimum level reached is 98.93m, which is 0.89m below the original bed level. Following the flood, the bed level in the constriction rises towards the equilibrium value for the low flow condition. The maximum depth of general scour was 0.89m, whereas steady discharge of $20m^3/s$ causes an equilibrium depth of scour of 1.15m.

Results for the shorter duration flood hydrograph are shown in Figure 15. It is clear that the depth of general scour during the short flood is less than during the long flood: the maximum depth of scour in this case is only 0.45m, compared with 0.89m in the case of the long flood. Following the flood, the bed level in the constriction tends to rise to the original low flow equilibrium level.

These tests show that flood duration can be an important parameter in determining the depth of general scour. Methods which do not take flood duration into account, but assume instead that the equilibrium depth resulting from the maximum discharge will be attained, may give an unrealistically high estimate of general scour.

The results described in this section may also have implications for bridge inspections. Underwater inspections are often carried out during low flow periods in the summer months, several weeks or months after periods of flood. These model experiments have shown that bed levels can rise following a flood, and the bed level observed during a low flow period may not represent the minimum bed level which occurred during a flood. The time taken for bed levels to rise following a flood was, in these experiments, of the order of 40 days (1000 hours). Thus an inspection during a period of low flow may fail to identify scour which took place during floods only one month previously.

4.3 Comparison with other methods

4.3.1 Steady flows

This section presents a comparison of the numerical model results with those from three formulae which are recommended for design of bridge openings against general scour due to channel constriction. The results of the comparison are presented in Table 1 and Figure 16

Farraday and Charlton (1983) present several equations for predicting the stable geometry of alluvial channels. In general, the width and depth of channel are expressed as functions of discharge and sediment properties. These equations are 'regime' equations based on observations of the dimensions of channels. General scour depth can be calculated by applying the formulae to the constricted reach. For the present comparison, the following formula was used to calculate the depths in the constricted reach, y:

$$y = 0.38*q^{0.7}D_{50}^{-0.17}$$

where q = unit discharge, discharge/channel width

D_{50} = sediment size

This is the equation given by Farraday and Charlton for sand bed channels. The depth of general scour was then deduced by subtracting the flow depth in the un-constricted part of the channel from the flow depth in the constricted part of the channel calculated from the above formula. The flow depth in the un-constricted part of the channel was obtained from the numerical model backwater calculations.

This method is completely unsuccessful in calculating general scour. The flow depths calculated by the 'regime' formula for the constricted reach are less than those calculated by the numerical model in the un-constricted part of the reach, and therefore, deposition is predicted in the constricted reach instead of erosion. The reason for the poor agreement is that the geometry of the channel used for the numerical model experiments does not match the dimensions given by the 'regime' formulae given in Charlton and Farraday. This indicates that the method may not be applicable in cases where the channel geometry in an un-constricted reach of a river is not similar to the geometry predicted by the regime formulae. This may often be the case.

Neill (1973) presents four methods for estimating general scour for design and analysis of general scour at constricted reaches of a river. The methods have different data requirements: for the present study the method based on a regime method using limited field measurements was chosen as the most appropriate. The method is used to calculate the depth of flow in a constricted reach, y, from the following formula:

$$y = y_{us}(qf/qi)^{m},$$

where
- y_{us} = upstream channel depth
- qf = flood discharge per unit width within constricted reach
- qi = bankfull discharge per unit width of channel, in un-constricted reach
- m = exponent depending on bed material, 0.67 for sand.

It was assumed for the present comparison that the flood discharge was equal to the channel discharge.

The depth of general scour was calculated from the above formula by subtracting the upstream depth, y_{us}, from the calculated scoured depth y.

A comparison of this method with numerical model results is shown in Figure 16. The numerical model predicts greater depths of scour. The regime method recommended by Neill predicts the correct trends of scour with constriction and discharge: increasing depth of scour with increasing constriction and with increasing discharge. The method takes no account of sand size however, unlike the numerical model which predicts that the depth of scour decreases with increasing sand size.

The final method for comparison is from the US Department of Transportation, Federal Highways Administration (FHWA), (1988). The report presents interim procedures for evaluating scour at bridges. For the case of general scour in a contracted section, a formula based on a method presented by Laursen in 1960 is recommended as being, at present, the best equation available. The formula is very similar to the Neill method, but sediment size is taken into account.

Predictions of general scour using the FHWA (1988) method are compared with those from the numerical model in Figure 16. The numerical model predicts greater depths of scour, but the methods are in agreement that scour increases with increasing constriction, increasing discharge and decreasing sediment size.

4.3.2 Unsteady flows

The existing prediction methods can take account of channel constriction, discharge and sediment size. They do not take any account of flood duration, and predict scour under steady flow conditions only. Numerical model results have indicated that floods can have an important effect on general scour.

4.4 Comparison with physical model results

Unfortunately, no measurements of general scour at real bridges were available for comparison, but the numerical model was used to simulate results of a physical model experiment. The model gave good agreement. The development of scour with time and the ultimate depth of general scour were both predicted accurately, giving further confidence that the numerical model described in this report is capable of representing the process of general scour.

5. CONCLUSIONS AND RECOMENDATIONS

Scour is a major cause of bridge failure and it is important to make quantitative predictions in order to design economical and safe foundations. One of the two types of scour caused by many bridges is general scour, which is a lowering of the bed level in the vicinity of a bridge due to a constriction in the river. Methods for predicting general scour are at present based on regime or empirical methods. These are limited by the variables which are considered, and by the range of conditions on which they are based. The aim of this study has been to investigate the feasibility of applying a numerical sediment transport model to prediction of general scour.

The study firstly considered steady discharge conditions. The numerical model successfully represented the process of general scour in a qualitative sense. Further testing and comparison with laboratory results are necessary to confirm that the model is capable of making accurate quantitative predictions. The numerical model results were compared with calculations using a number of recognised scour prediction formulae which are recommended for design and analysis. The model predicted greater depths of scour than were calculated using these formulae.

Further tests were carried out to examine whether the model can accurately represent the effect of unsteady flows on general scour. It has been shown that the duration of a flood can affect maximum scour depths, and that scour due to floods will in general be less than scour due to steady discharges with the same value as the peak flood discharge. Further testing is necessary to examine the effect of unsteady flows on general scour.

In order to represent scour at many real bridges, the model should be able to represent graded sediment, instead of assuming that the bed material is of uniform size. The model could then be used to predict the effect of armouring, whereby scour has the effect of increasing the proportion of coarse material in the bed. Armouring can reduce the equilibrium depth of scour. HR experience in modelling graded sediments could be applied.

In order to verify the model, a more detailed comparison with laboratory and field measurements should be made. If appropriate data does not already exist, this would entail a field study to monitor one or more bridges at times of flood. In the past it has been difficult and expensive to measure scour during a flood, but an instrument currently under test at HR may provide an economical means of monitoring the time-varying development of general scour. These field measurements would be used to verify and refine the model for application at real bridges.

The aim should be production of design guidelines based on experiments carried out with the verified numerical model. This would provide engineers with a more accurate and rational method for design against general scour than is presently available.

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TABLE

TABLE 1 : Comparison of numerical model results with general scour formulae

Experimental conditions			Depth of general scour (m)			
Constriction	Discharge (m^3/s)	Sediment Diameter mm	Calculated	Farraday+ Charlton	Neill	FHWA
0.9	20	0.5	0.51	-1.36	0.37	0.37
0.8	20	0.5	1.15	-1.05	0.83	0.81
0.7	20	0.5	1.95	-0.67	1.38	1.36
0.8	10	0.5	0.66	-0.42	0.48	0.46
0.8	15	0.5	0.90	-0.72	0.66	0.64
0.8	20	0.5	1.15	-1.05	0.83	0.81
0.8	20	0.3	1.26	-0.69	0.83	0.85
0.8	20	0.5	1.15	-1.05	0.83	0.81
0.8	20	0.7	1.09	-1.28	0.83	0.78

FIGURES.

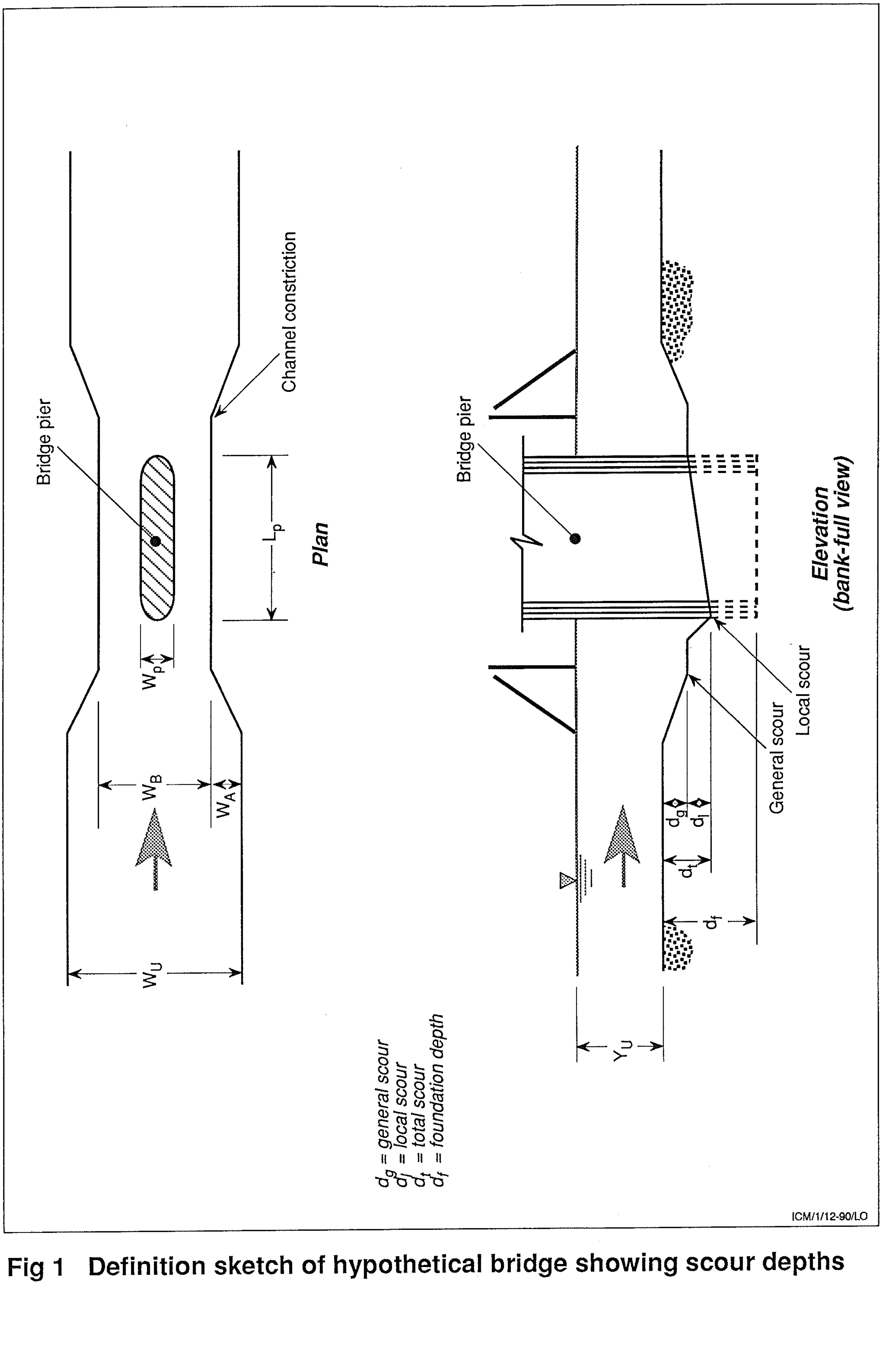
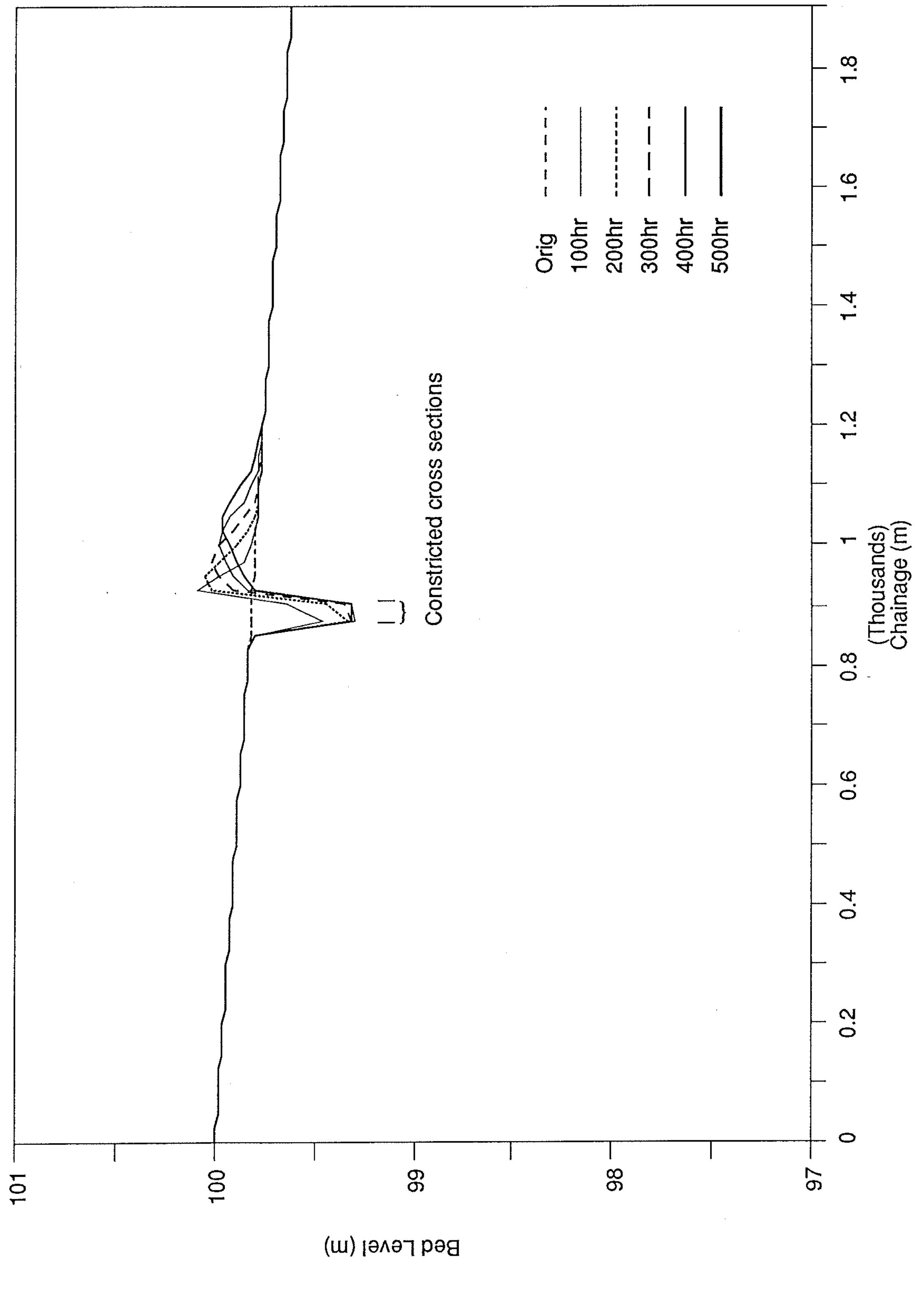
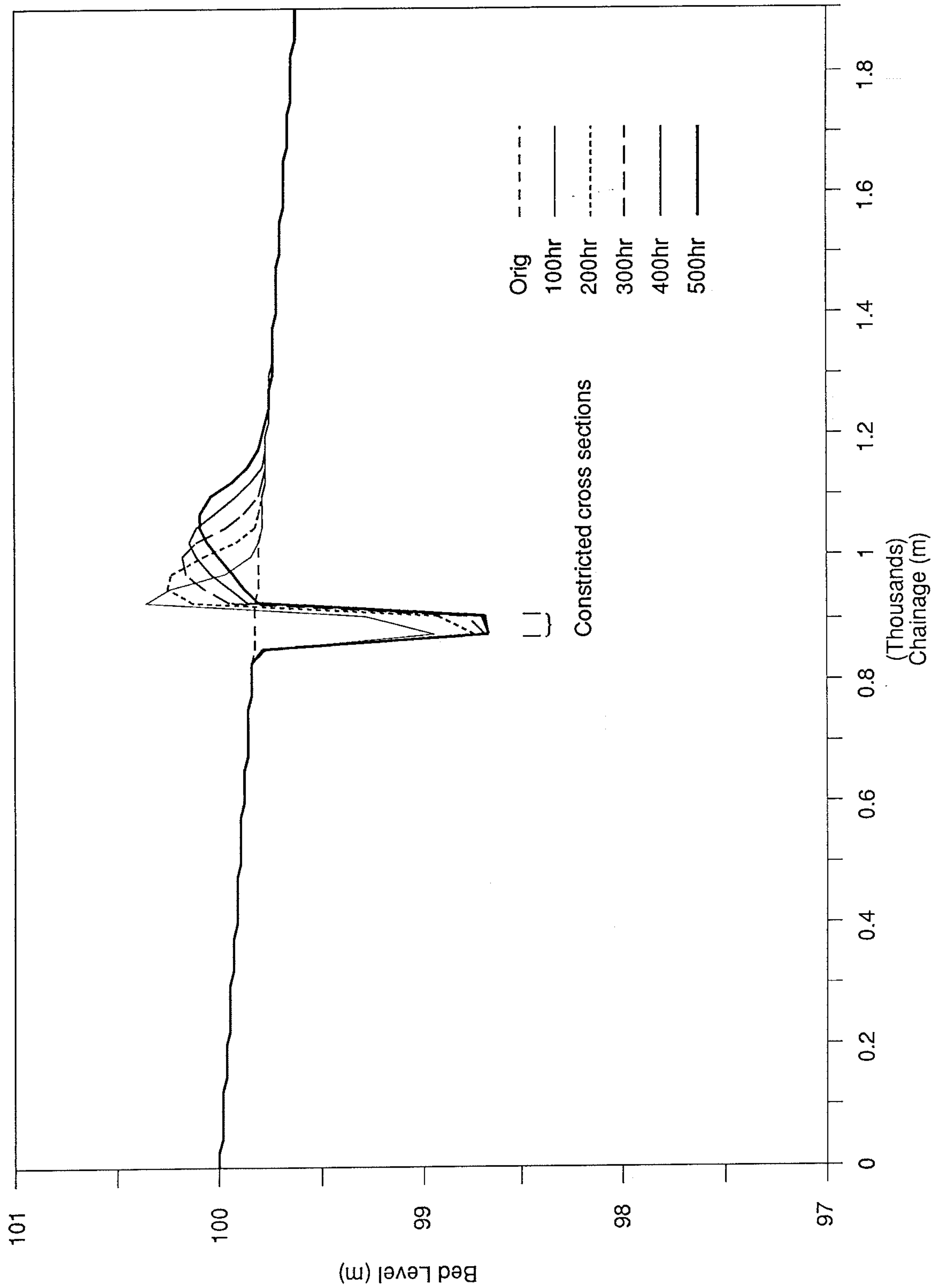


Fig 1 Definition sketch of hypothetical bridge showing scour depths



IM/FIG 2/1/11/90/IB

Fig 2 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 1. Constriction 0.9



IM/FIG 3/1/11/90/IB

Fig 3 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 1. Constriction 0.8

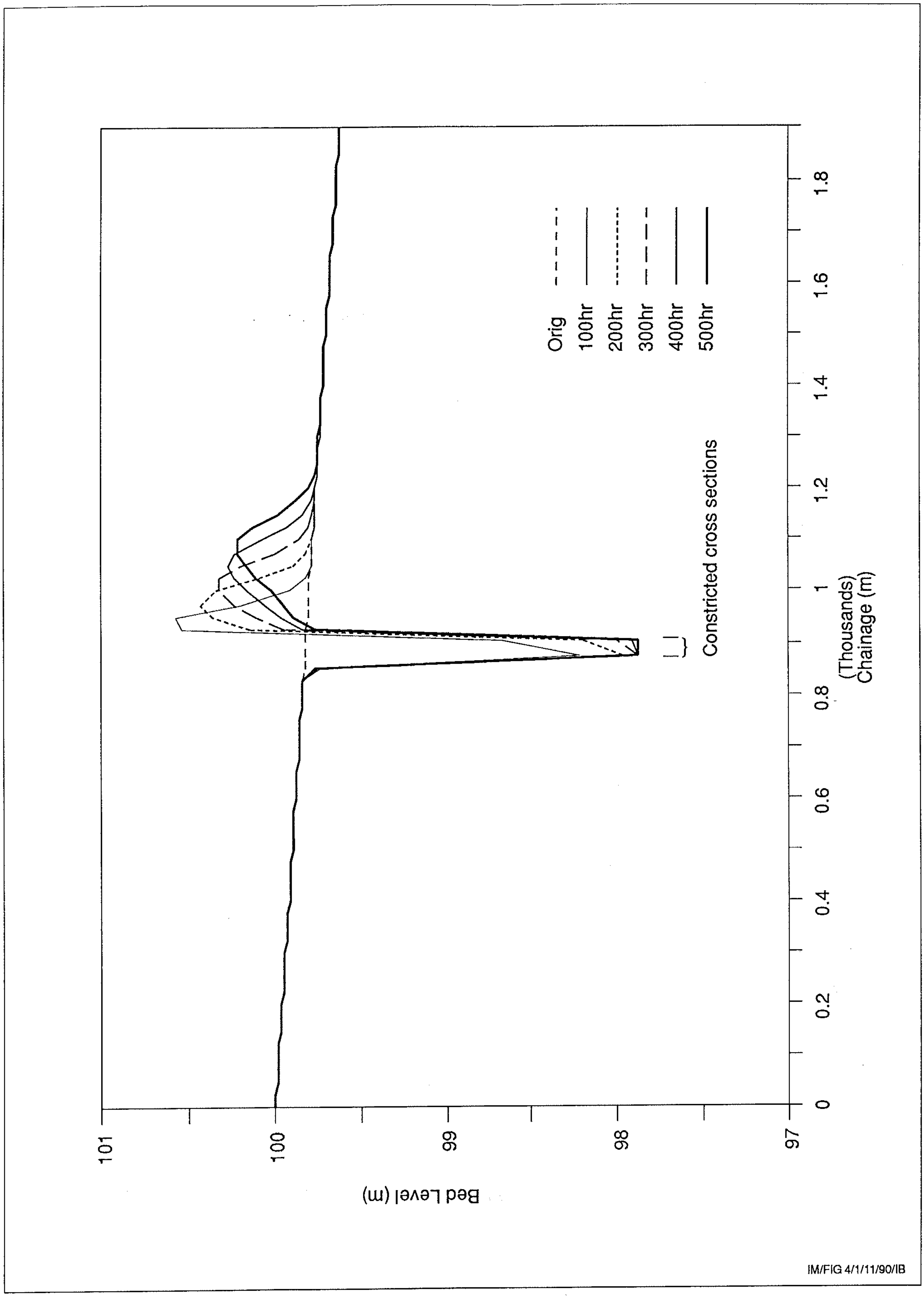
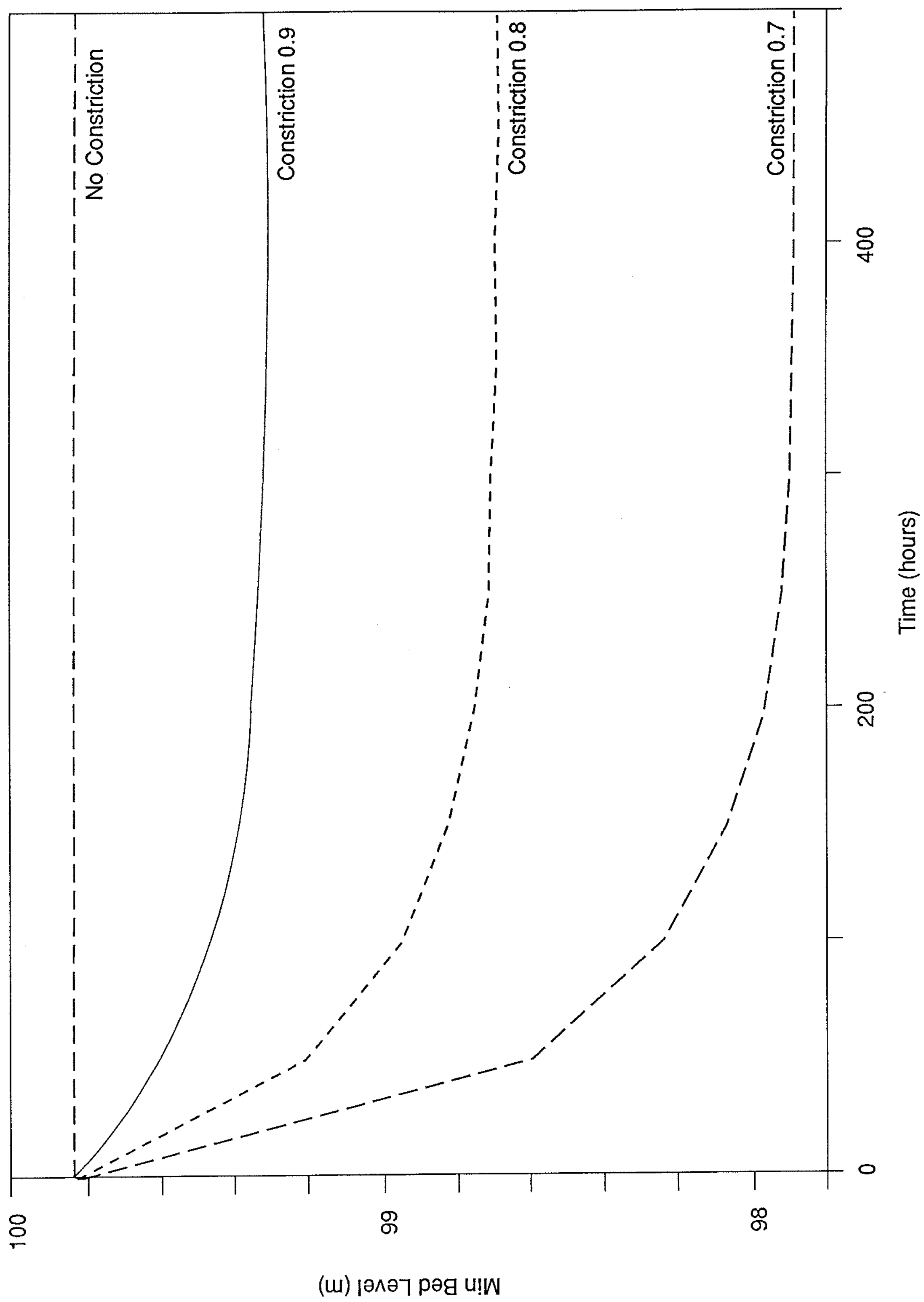


Fig 4 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 1. Constriction 0.7



IM/FIG 5/1/11/90/IB

Fig 5 Minimum bed level in constricted reach: effect of different channel constrictions: Series 1

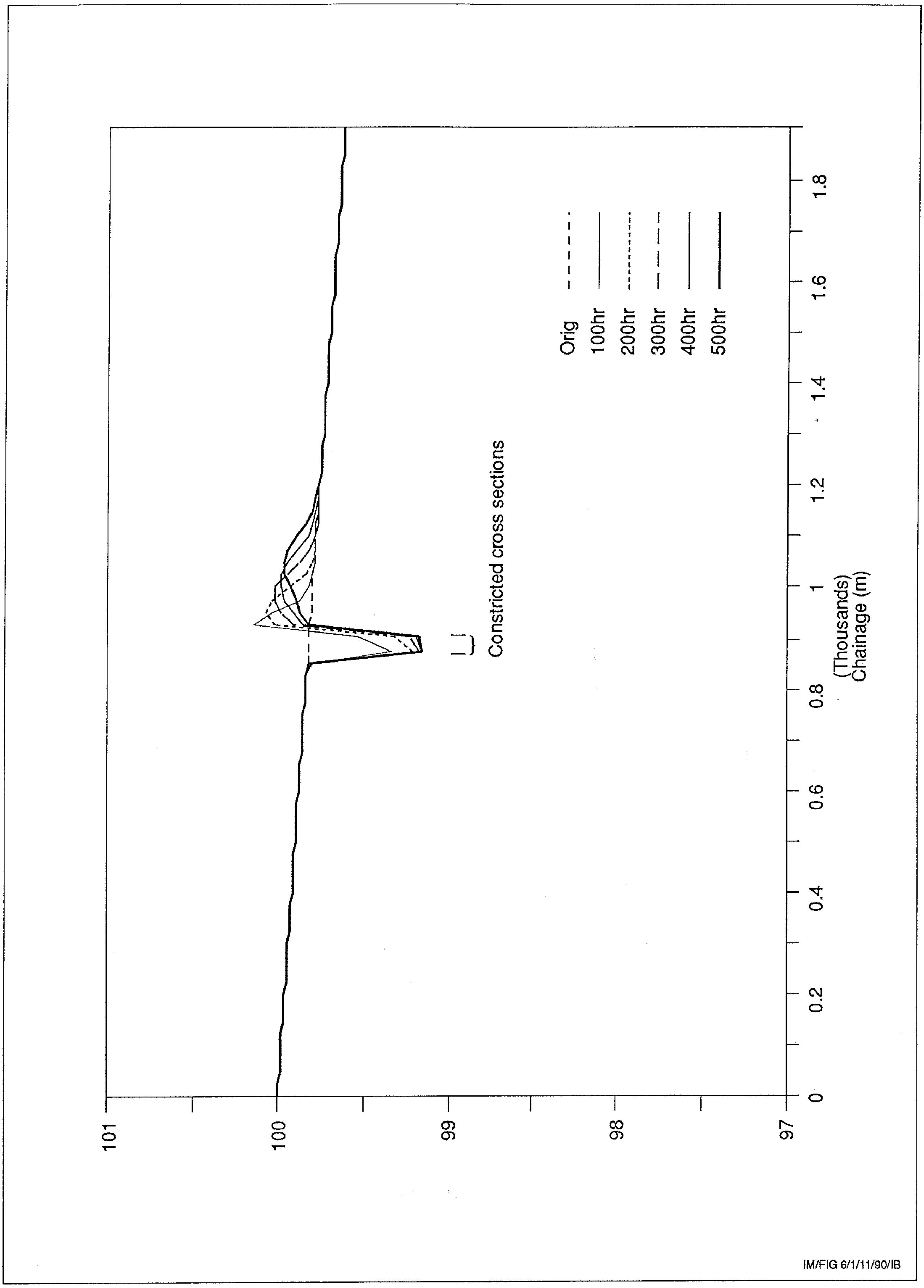
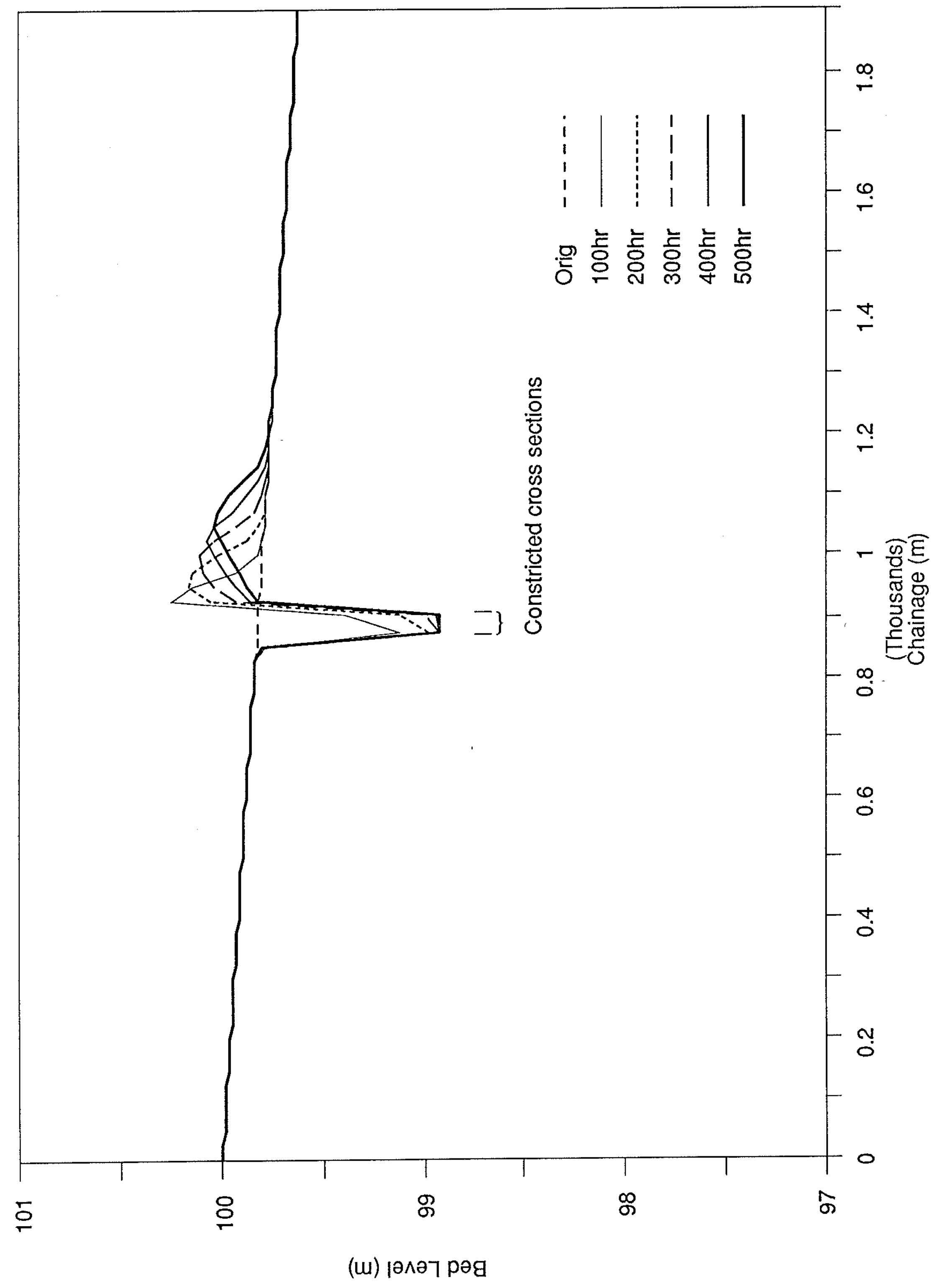
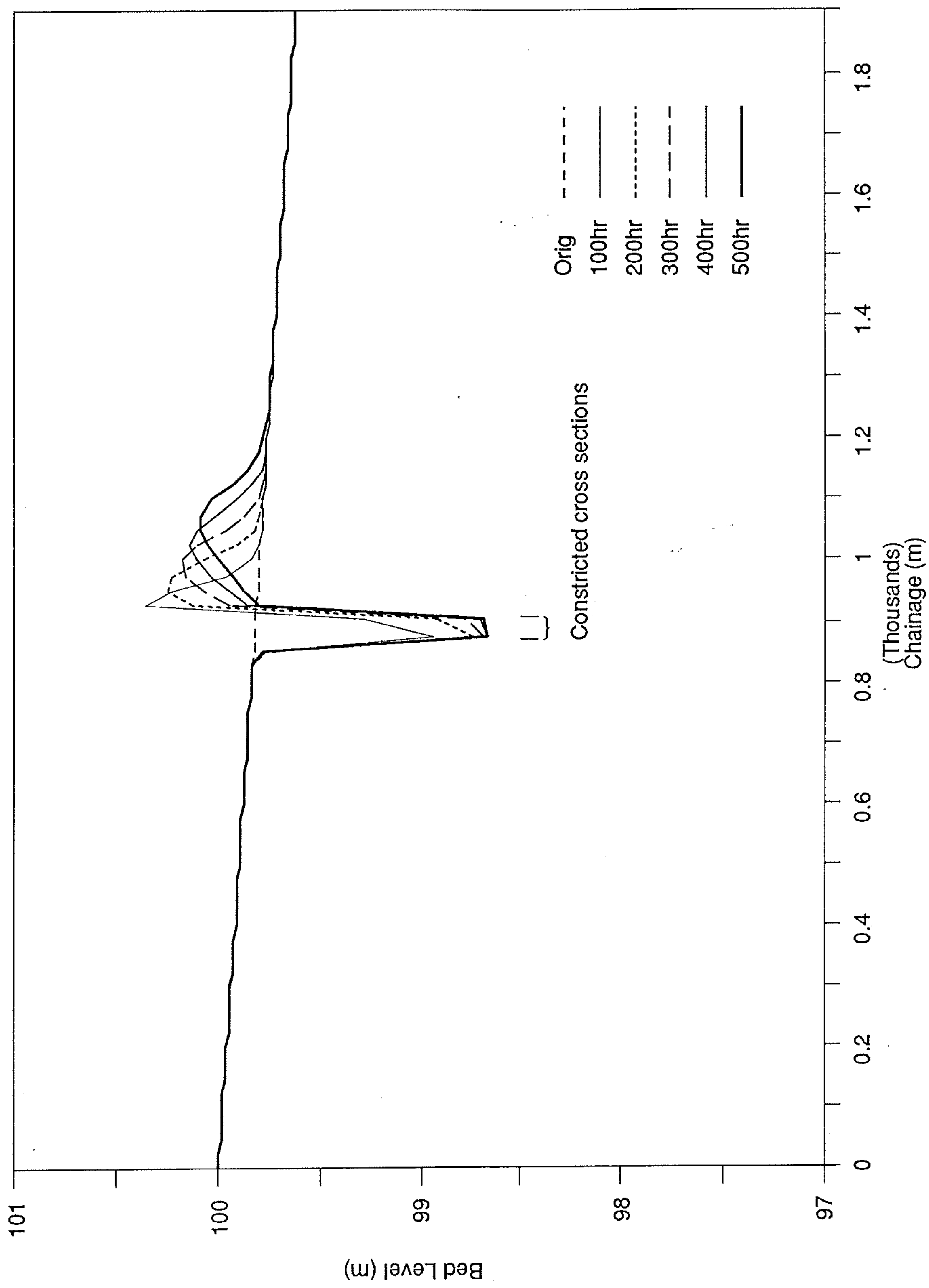


Fig 6 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 2. Discharge = 10m^3/s



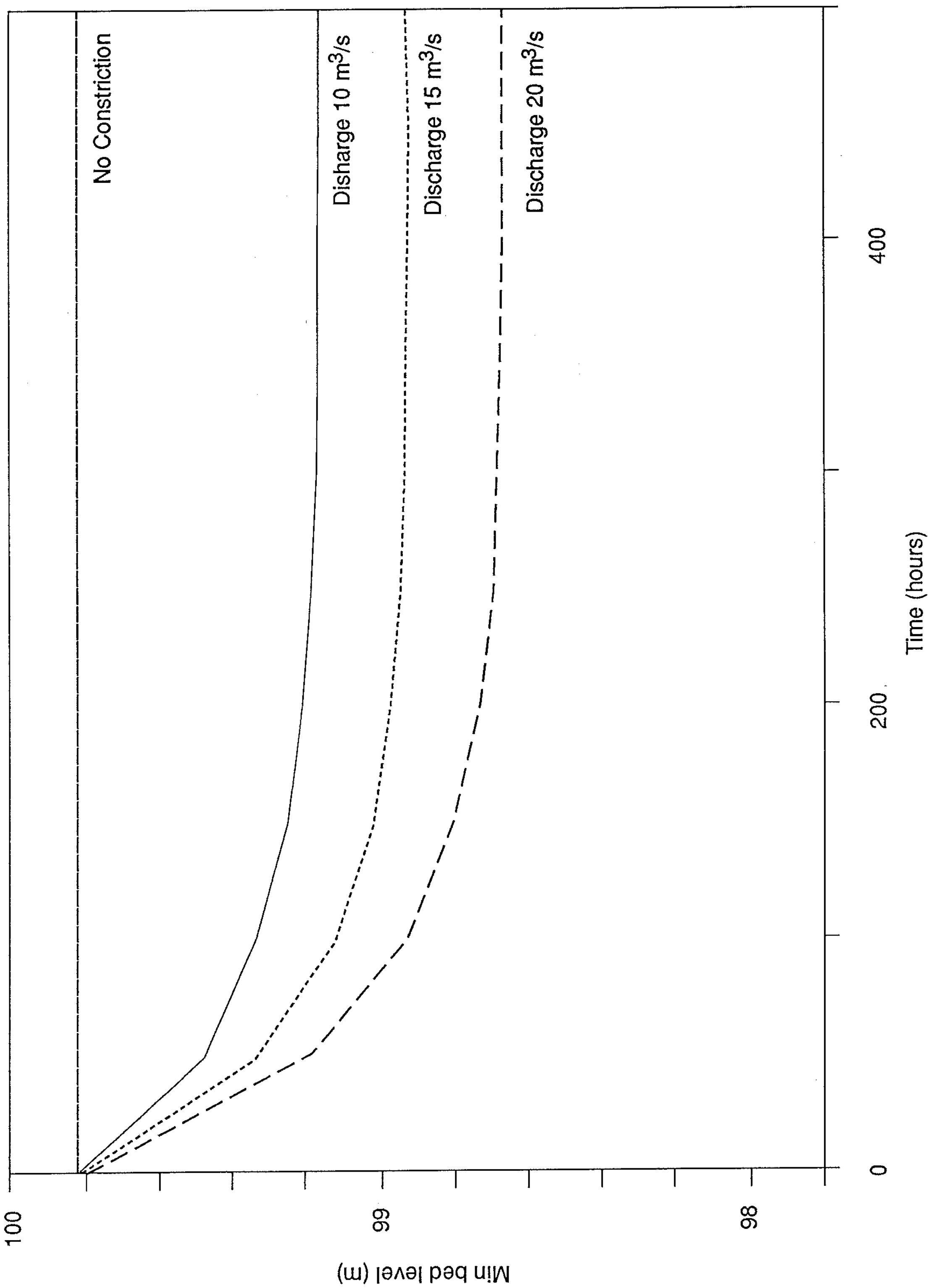
IM/FIG 7/2/11/90/IB

Fig 7 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 2. Discharge = $15m^3/s$



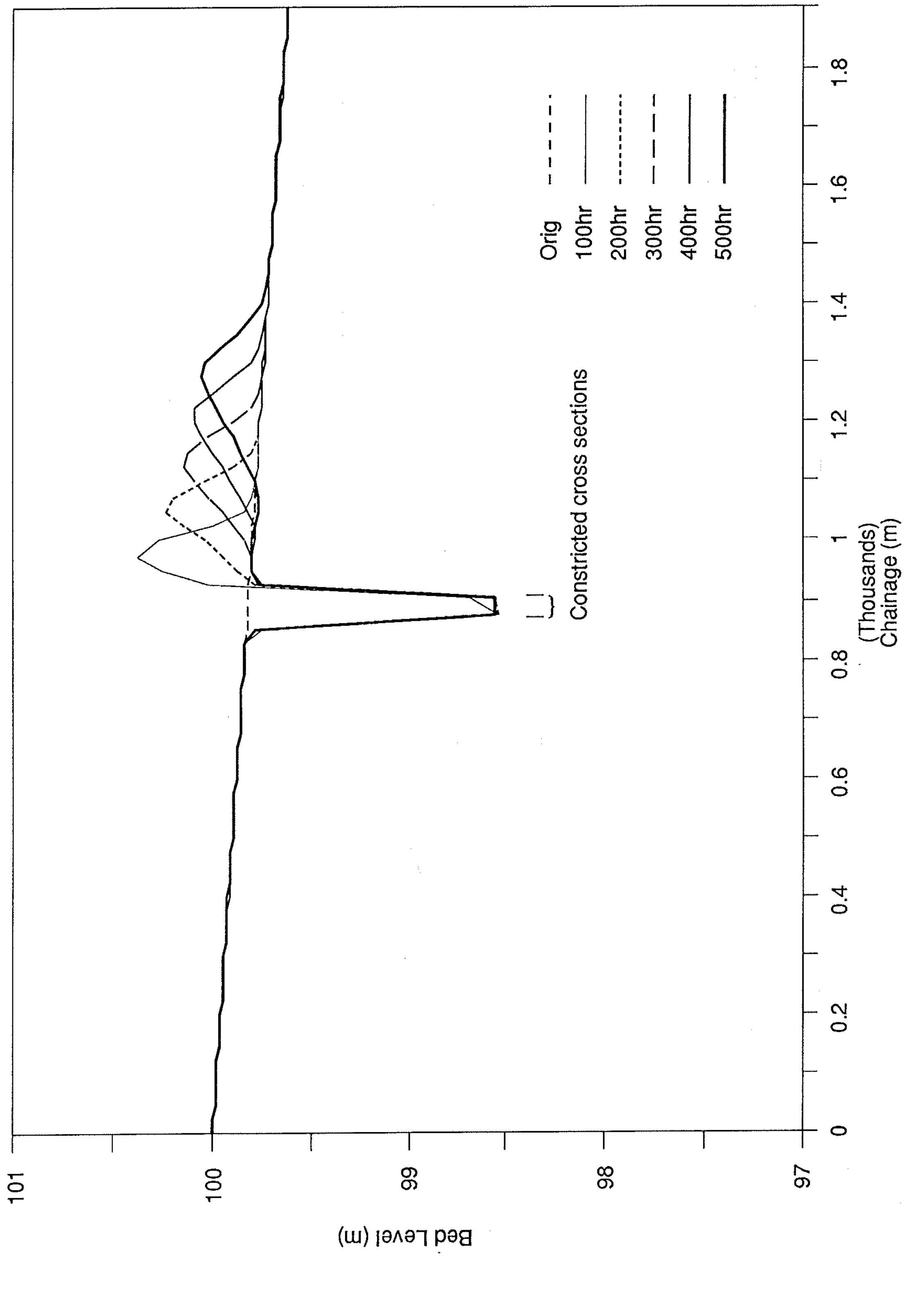
IM/FIG 8/2/11/90/IB

Fig 8 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 2. Discharge = 20m^3/s



IM/FIG 9/2/11/90/IB

Fig 9 Minimum bed levels in constricted reach: effect different discharges: Series 2



IM/FIG 10/2/11/90/IB

Fig 10 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 3, Sediment size 0.3mm

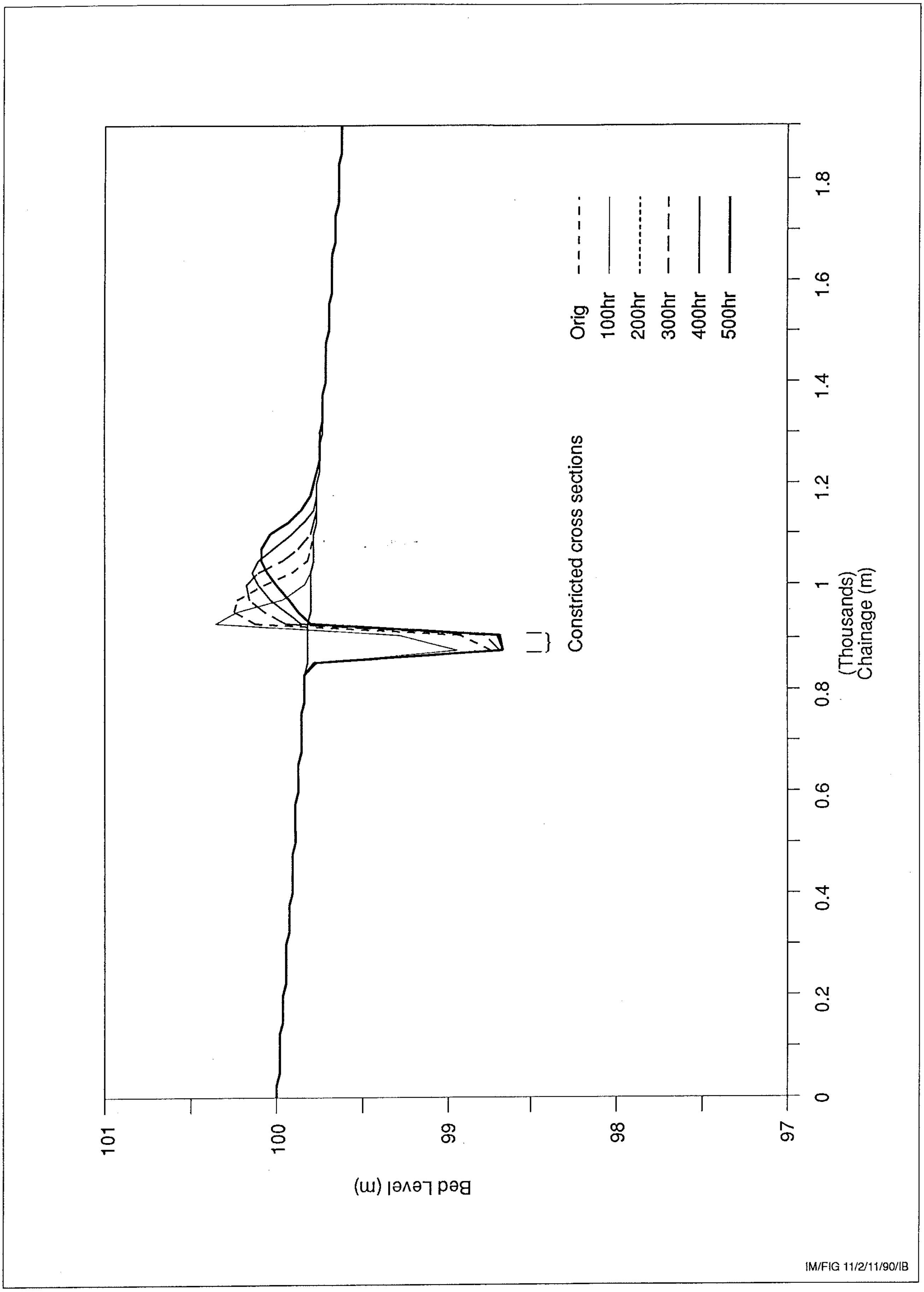
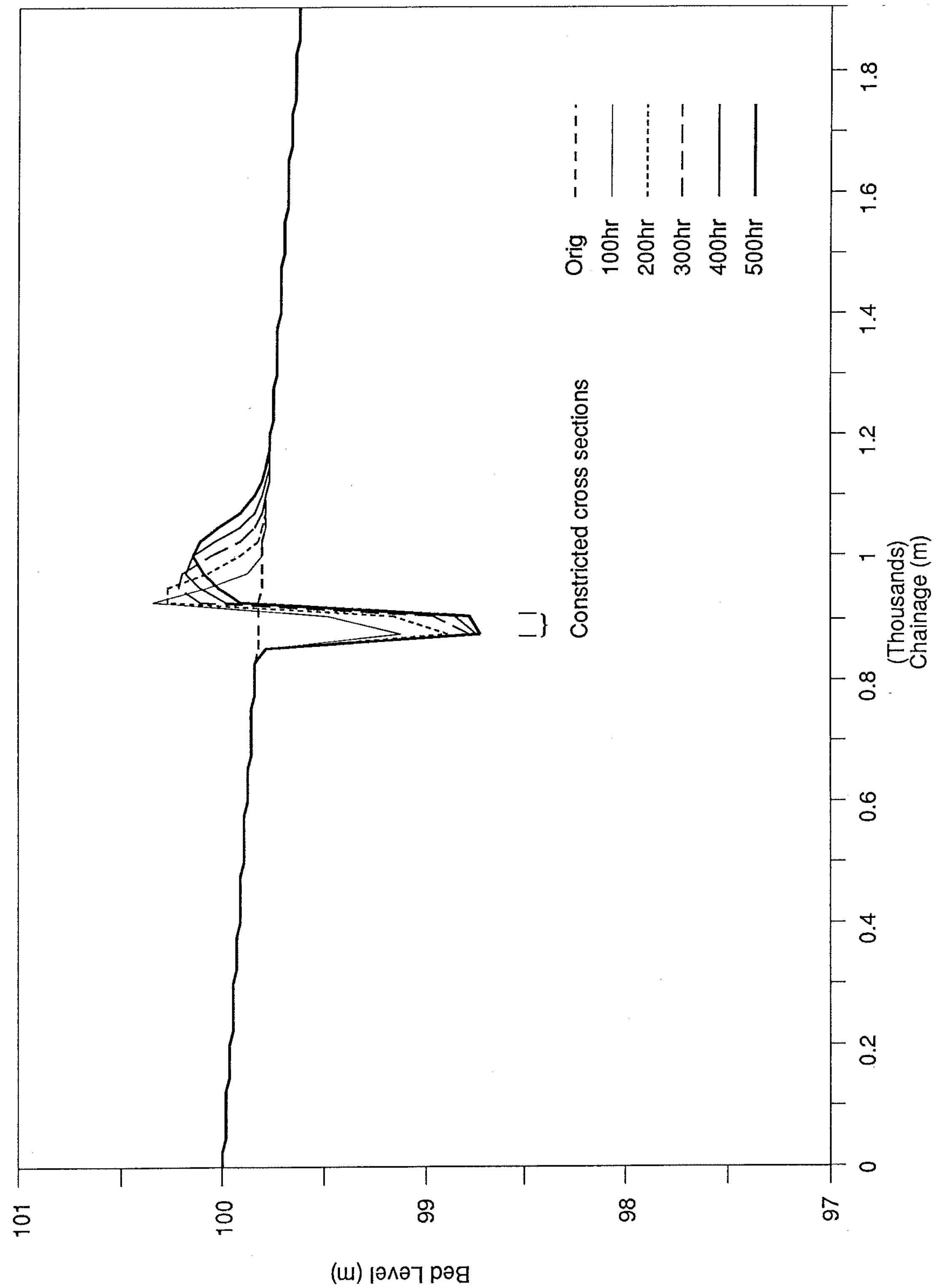
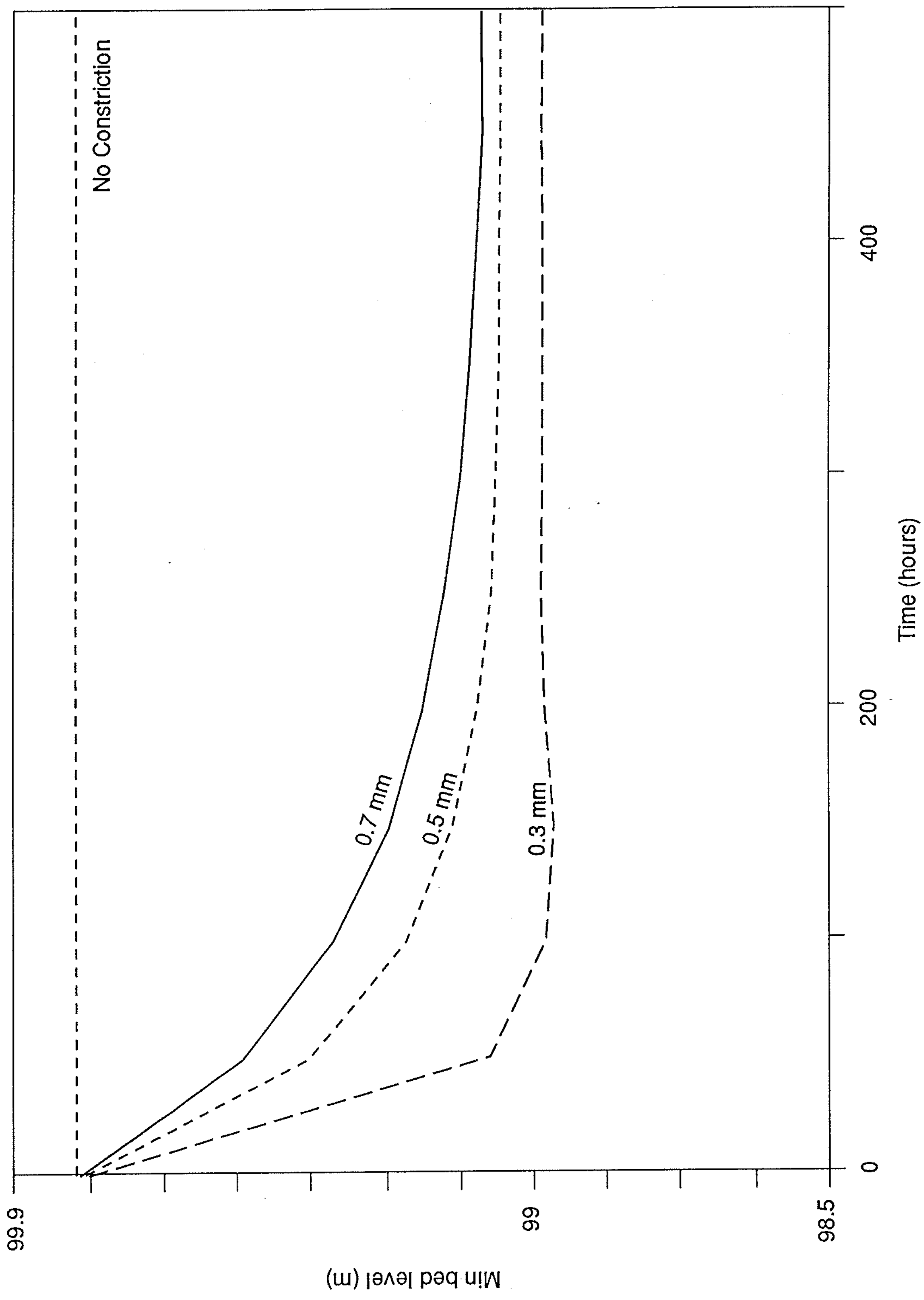


Fig 11 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 3, Sediment size 0.5mm



IM/FIG 12/2/11/90/IB

Fig 12 Numerical model predictions of general scour showing development of longitudinal profile with time. Series 3, Sediment size 0.7mm



IM/FIG 13/2/11/90/IB

Fig 13 Minimum bed levels in constricted reach: effect of different sediment sizes: Series 3

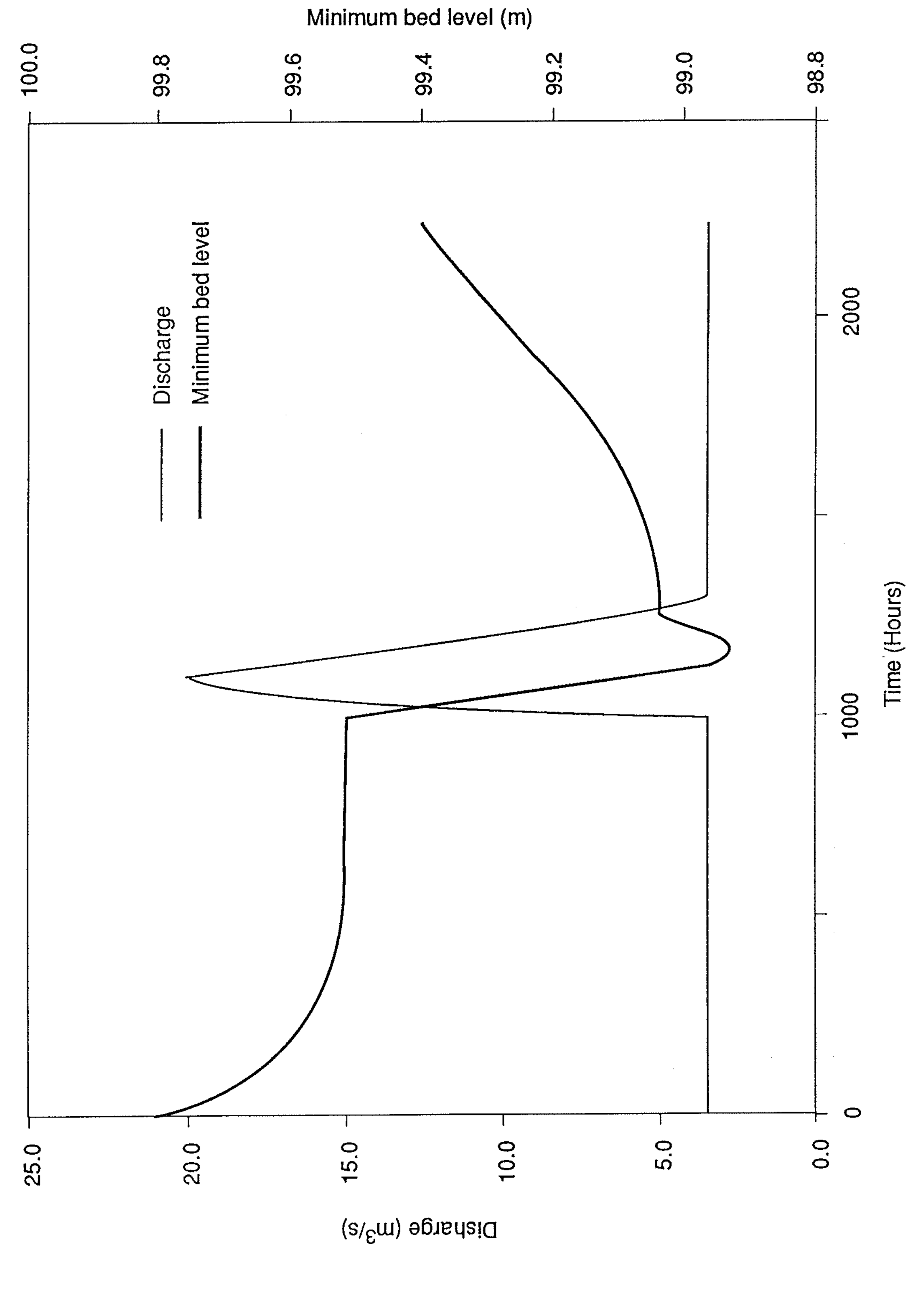


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Fig 14 300 hour flood hydrograph: Variation of minimum general scoured bed level with time, numerical model results

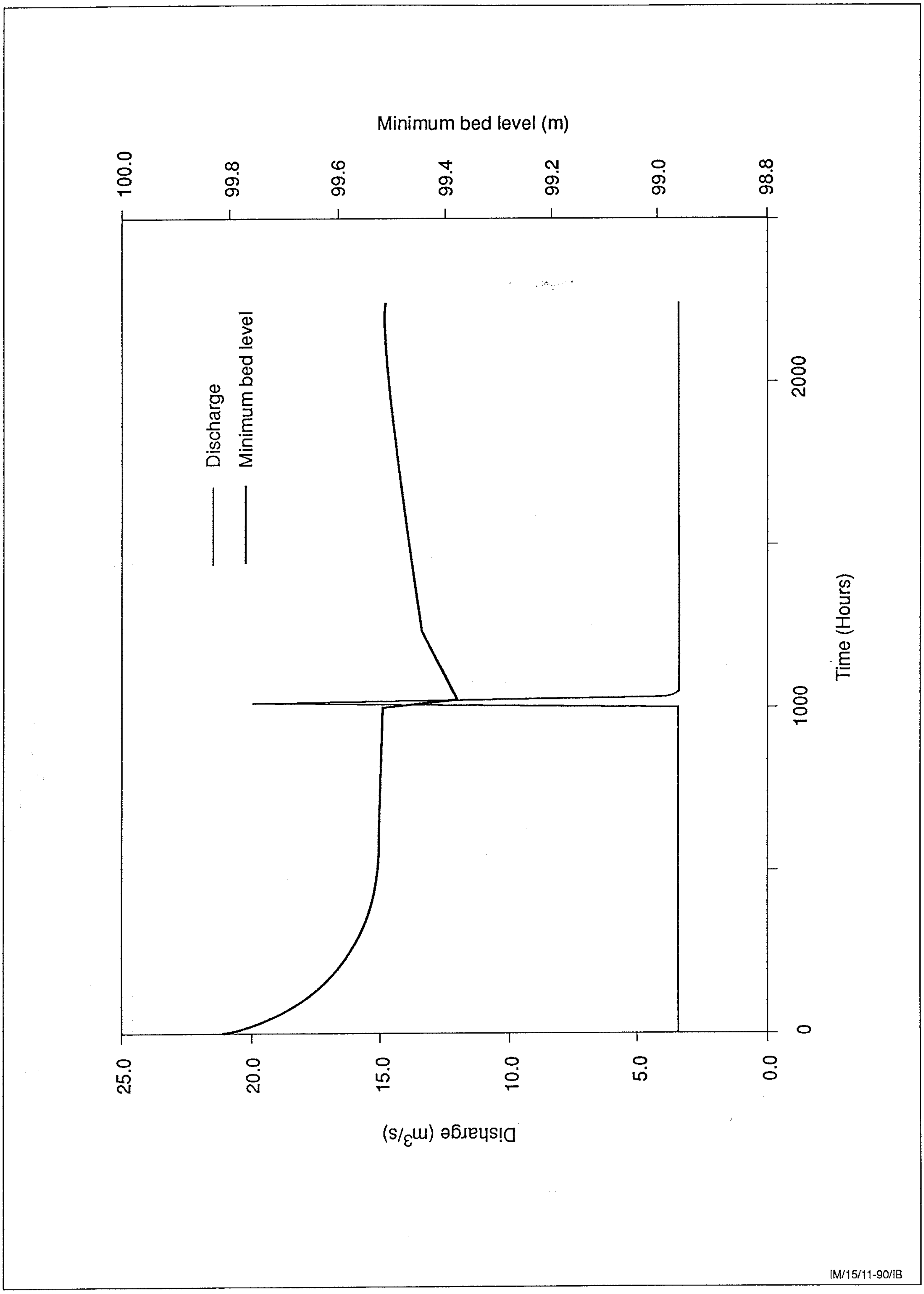

Fig 15 30 hour flood hydrograph: Variation of minimum general scoured bed level with time

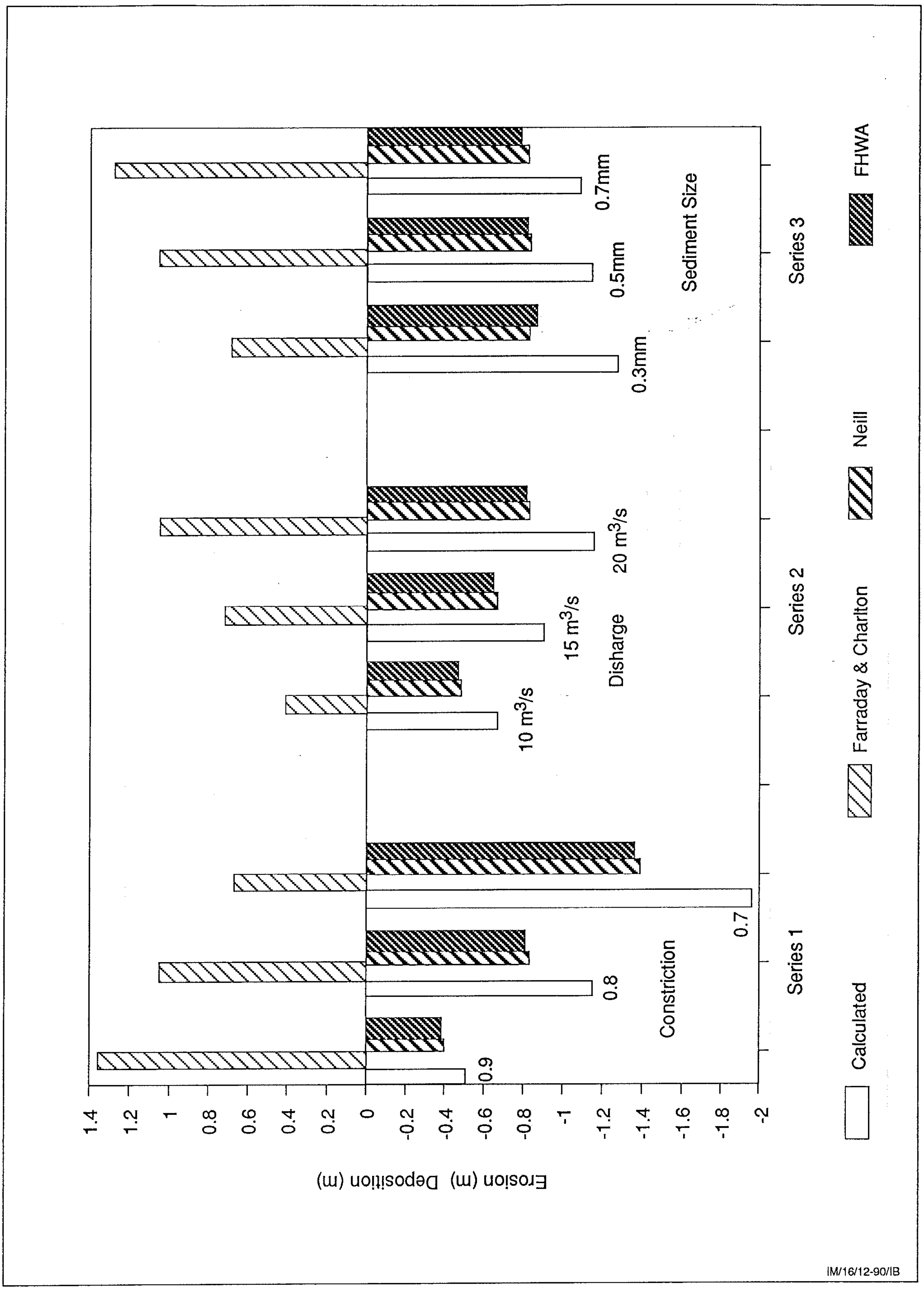

Fig 16 Comparison of numerical model results and contraction scour formulae