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A Review of Predictive Methods for General Scour

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Abstract

General scour is the bed level change that can take place in a river section below the natural or normal bed level. Predicting the amount of general scour has received less attention than predicting local scour but as the two effects are additive it is equally as important. The methods used to predict general scour are frequently based on either a regime approach or on conditions for the initiation of motion of the sediment on the bed of the channel. In the paper existing methods of estimating general scour are critically reviewed. Numerical model results are presented indicating that the amount of general scour that takes place during a single flood event depends upon the duration of the flood event and that in many cases equilibrium scour depths are never achieved. This implies that in many cases the assumptions underlying methods for predicting general scour are not satisfied in the field.

1 Introduction

In designing bridge or pipeline crossings of rivers an important design parameter is the bed levels which may occur in the river during the lifetime of the structure. For bridges a lot of attention has been paid to the issue of predicting local scour around structures, perhaps because this is a well-defined and obvious problem which may be studied using laboratory experiments and more recently using numerical models. The issue of predicting general changes in river bed level has received less attention.

There are a number of potential sources of general bed level change:

Long-term progressive degradation , either natural or man-induced may take place.

Changes in channel shape arising from:

a) a change in the river type, for example, a change from a braided to a meandering river,
b) a change in the plan form of a river, for example, a change in the radius of curvature of the river channel,

Changes caused by individual flood events.

It is the last topic, the changes in bed level arising during a flood event that will be discussed in this paper.

2 Definition of general scour

As alluded to above, the changes in bed level that may occur during the lifetime of a structure potentially arise from a number of different sources and so can be difficult to define. Thus different authors use different definitions and classifications. Melville and Coleman (2000) define general scour as ‘that scour occurring irrespective of the presence of any human-imposed structure’ while they define contraction scour as that scour that ‘can occur where the foundations and/or the road approach embankments of a bridge restrict the waterway. Alternatively, contraction scour can occur if the bridge is sited at a natural contraction in the width of the river.’ Thus there is an overlap between the Melville and Coleman definitions of general scour and contraction scour.

In the following we will discuss that scour that can arise as a result of longitudinal changes in channel properties resulting from either man-made structures or natural changes. Thus this corresponds to the Melville and Coleman definition of contraction scour

3 Properties of general scour

The factors which affect contraction scour include:

a) Change in cross-sectional area of flow

   It is normally assumed that the contraction is brought about by a reduction in the width of the flow. The corresponding adjustment to the bed leads to the scour. This factor is normally quantified using the parameter B1/B2, where B is the width of the channel and 1 refers to the upstream section and 2 refers to the downstream section.

b) Change in discharge

   Continuity imposes that unless water is being lost out of the system that the discharge at the constricted reach must be the same as the total discharge at the upstream section. As has been pointed out, however, particularly at bridges with approach embankments, the flow upstream may be distributed between the main channel(s) and the floodplains while at the constricted section all the flow may be confined to the main channel. Thus the discharge in the main channel between the upstream and constricted sections may be different.

c) Sediment grading

   Where the bed sediment contains a range of sediment sizes, differential transport of different sizes may lead to the bed in the constricted section armouring and so leading to a reduction in the scour depth in comparison with a uniform sediment

d) Sediment supply from upstream

   The amount of sediment that is being transported by the channel can also affect the depth of scour. Thus in the past a distinction has been made between ‘clear water’ and ‘live-bed’ scour. It is generally considered that clear water scour in which there is no sediment input from upstream will be larger than live bed scour when there is some sediment supply from upstream

e) Duration of flow

   Many theories to predict scour are based on the assumption of equilibrium conditions. Thus it is assumed that an individual flood event is sufficiently long that the scour achieves its ultimate depth. It is now clear that following a flood event the bed of the river rapidly recovers to the pre-flood bed levels. For short duration flood events the scour may not achieve equilibrium conditions.

4 Review of predictive methods

4.1 Long contraction methods

Many approaches to the problem of predicting contraction scour are based on considering a long rectangular contraction. This assume that the upstream section is uniform and rectangular and that the length of the contraction is long enough tom establish uniform conditions in the contraction. The objective is then to predict the conditions in the contracted section and relate them to the upstream conditions. The approach seems to have been first used by Straub (1934) and subsequently extended by Laursen (1958, 1960, 1962 and 1963), Komura (1966), Ashida (1964), Gill (1981) and Keller (1983). To make this approach analytically tractable a number of assumptions have to be made:

a) the length of the contraction is long enough to establish uniform conditions
b) the energy slope in the contracted section is the same that in the upstream section
c) the flow conditions in the contracted section are such that the sediment is just at the point of initiation of motion.

Determine the critical velocity an estimate is required of the Manning's n value for the channel. This is based on the sediment diameter using Strickler's equation:

$$n = 0.034\ D_{50}^{1/6}. \qquad (1)$$

This assumes that the hydraulic roughness is predominantly skin roughness due to the sediment grains. This is often a reasonable assumption for gravel bed rivers but can underestimate the hydraulic roughness for sand bed rivers where form losses may be significant. Even for gravel bed rivers, the use of D_{50} in assessing the hydraulic roughness of a sediment bed is also rather unusual. In the context of gravel bed rivers it is normally found that the hydraulic roughness depends upon the size of the larger fractions such as the D_{90} or D_{85}. These problems may explain a subsequent recommendation that in equation (1) D_{50} should be replaced by D_m, where:

$$D_m = 1.25\ D_{50}.$$

Though one can understand the logic of using a sediment diameter larger than the D_{50} size it seems unlikely that a simple factor of 1.25 is an adequate representation of the different processes at work.

The impact of underestimating the Manning's n value is that the scour depth is also then underestimated.

Laboratory simulations of long contractions have shown that the theories give reasonable predictions of the depth within the constricted section but tend to under-estimate the observed depths. Keller presented a generalisation of the analysis of Laursen (1963) and found that it under predicted the observations by up to 13%.

Keller recommends that for design purposes the predictions of the equations should be multiplied by 1.2.

While the long contraction model is attractive to enable an analytic expression for scour depth it may not be a very realistic model of contraction scour at crossings. Where the contraction is due to a bridge and abutments its streamwise extent is rarely long enough to establish uniform conditions in the contracted reach. Nor is it is clear that in the real world the second assumption above about energy slope is valid.

Keller (1983) observed that in some of the laboratory experiments the scour at the entry to the contraction exceeded that in section where the flow had become uniform once again. This increased scour at the entry to the contraction can arise from a number of causes. In general the contractions at crossings are so short that uniform conditions are rarely established in the contracted section. The result is that in the contracted section the energy slope exceeds that in the section upstream and downstream. In abrupt contractions the flow may separate from the sides of the channel. This results in the formation of a horizontal, transverse recirculation zone. A vena contracta is present that is narrower than the width of the contracted section. This means that the effective width of the cross-section is reduced from the bank to bank width. This effective narrowing of the section will depend upon the details of the transition from upstream to downstream and will be larger in sudden transitions and less in more gradual transitions. It is likely that some estimate of the additional scour caused by this effect could be provided by estimating the width of the vena contract. Certainly an upper limit on this effect could be provided by assuming a sharp transition.

The evidence is thus that methods of estimating scour based on a long contraction approach are likely to underestimate the depth of scour.

4.2 Regime methods

Another approach to estimating contraction scour has been based on regime theory. Neill (1973) suggested that the depth of a flow in a channel during a flood could be determined using the regime theory due to Lacey (1973). This provided a method for predicting the depth in an uncontracted channel.

Previously Blench (1969) had put forward a regime approach to calculating the scour depth in a constricted channel. In this approach instead of using the discharge as the independent variable, the unit discharge is used to determine the depth of flow. Blench used the regime equation of the form:

$$V^2/d = F_b, \qquad (2)$$

where Fb is a function of the sediment. By using the equation:

$$q = Vd, \qquad (3)$$

where q is the unit discharge, the regime equation (2) becomes:

$$d = (q^2 F_b)^{1/3}. \qquad (4)$$

It would appear that Blench then proposed using this equation within the contraction to determine the depth of flow. This approach neglects the fact that equation (2) is a description of regime channels in which the flow width is free to adjust and is thus related to the other flow parameters, V and d. It does not necessarily apply, however, to channels with constrained widths. Thus equation (4) is only applicable to regime channels and does not apply to channels whose width is constrained. It thus cannot be used to predict contraction scour. This can be easily demonstrated by using the data from the laboratory experiments of Keller. All the experiments used the same sediment and so the value of F_b should be constant. Thus the value of V^2/d should be the same for all the runs. In reality the value of V^2/d varies from 0.856 to 2.649. When equation (4) is used to predict the results of the experiments the errors range from 28 to 49%. Thus the regime approach of Blench cannot be recommended for use to predict constriction scour.

The regime approach has recently been refined by May et al (2002). Although not explicit this approach makes a number of assumptions. It assumes:

a) the length of the contraction is long enough to establish uniform conditions

b) the energy slope in the contracted section is the same that in the upstream section.

The method is based on assuming that the upstream section of the channel is in regime and that in the constricted reach the area of flow is the same as that in the upstream reach. As was discussed above these assumptions are not always valid for contractions associated with crossings.

4.3 Competent velocity methods

Competent velocity methods are based on the assumption that scour will continue until the flow conditions approach those for the threshold of motion of the bed sediment. As the name implies the flow conditions for threshold of motion are expressed in terms of a critical flow velocity. We know from the work of Yalin (1977) that using flow velocity to determine critical conditions is not very reliable in comparison with using critical shear stress. Thus any estimate of scour depth using competent velocity methods must be regarded with suspicion. As described under the section on long contractions it is possible to use an estimate of the Manning's n value to overcome this problem but errors in estimating Manning's n may add to the errors in estimating scour depths rather than reduce them.

4.4 Armouring condition

One disadvantage of the methods described above is that they assume that the composition of the bed material remains constant during the flood event. It seems likely that where the bed of the river consists of a range of sediment sizes that the finer sediment is preferentially removed and so the composition of the surface or armour layer changes during the flood. Particularly when there is partial transport so that not all the sediment sizes are moving, this may inhibit the development of scour and hence lead to smaller scour depths than would be obtained in uniform sediments with the same D_{50} size.

It should be noted that in scour equations such as those of Laursen, the depth of scour is a function of the sediment diameter and reduces as the sediment diameter increases. During a flood, differential sediment transport of different sediment sizes will lead to a change in composition of the bed sediments within a constriction. This will, in general, lead to an increase in size of sediment on the bed which will act to inhibit scour. Note that this effect will take place even if all the sediment sizes are moving.

A number of approaches have been based on assessing the degree of armouring that will take place. In essence they are based on a critical flow approach but take account of the fact that with time the composition of the bed will change so modifying the critical velocity. The methods of Pemberton and Lara (1984) and Borah (1989) are only applicable where a proportion of the bed material is sufficiently large that it is not moved by the flow.

Pemberton and Lara (1984) assume that the degraded channel has the same hydraulic conditions as the existing channel. This neglect the fact that as the scour takes place the velocities in the constricted channel will reduce. It is thus likely to over-estimate the depth of scour.

In cases where the bed of the river rapidly armours with immobile sediment this is likely to lead to increased shear stresses on the river banks and hence may lead to erosion of the river banks.

4.5 Empirical methods

There are a number of empirical methods such as the New Zealand Railways method (Holmes, 1974). The method is based on field data collected in New Zealand from scour failures at a number of railway bridges. The ability of empirical equations to make realistic assumptions depends upon the basis of the form of equation used to develop the relationship. In the case of the New Zealand Railway method Neill (1987) has criticised the physical basis of the method.

4.6 Equilibrium/non-equilibrium theories

All the approaches described above assume that the duration of a flood is long enough for equilibrium conditions to be achieved. There is evidence to suggest that in many rivers the duration of the flood is not long enough for the bed to scour down to the equilibrium values. Whether equilibrium values are achieved depends upon the product of the unit discharge and the difference in sediment concentration between the upstream reach and the contracted reach and the duration of the flood. Particularly for flashy rivers with low sediment concentrations, the equilibrium value may not be achieved.

Gole and Chitale (1967) carried out studies at two bridges in India and found that the full contraction scour depth, as given by equations for scour in long rectangular contractions, was not developed at abridge where the flood hydrograph was of short duration. This is consistent with some numerical modelling carried out by Meadowcroft (1991).

Meadowcroft modelled a hypothetical bridge and subjected it to a number of different discharge hydrographs with the same peak discharge but different time bases. In all cases the channel width was 5 m and the initial bed slope was 0.0002. A total of 77 cross-sections at 25m spacing were used to represent a 1,900m length of channel. A constriction was modelled by reducing the width of two adjacent sections, 875m and 900m from the upstream boundary. A sediment size of 0.5 mm was assumed. For the results presented here a channel constriction of 0.8 was assumed.

Figure 1 shows the time development of scour for long duration flood events in which the discharge is kept constant in time at a value of 20 m^3/s. The model indicates the development of equilibrium conditions and the time that is required to achieve such an equilibrium. Figure 2 shows the discharge hydrograph and the corresponding calculated minimum bed level. The duration of the flood event is 300 hours. The model clearly shows that bed levels recover after the peak of the flood has passed. This implies that inspections after floods may not indicate the depth of scour that may have taken place during the peak of the event. A duration of 300 hours for a flood event on a small river would be unusual in the UK. Figure 2 shows the minimum bed level generated by a flood of the same magnitude as that in Figure 1 but with a duration of 30 hours, which might be more typical of rivers in the UK. It can be seen that the scour depth developed is significantly smaller than the equilibrium scour depth. This suggests that equilibrium scour theories may over-estimate the scour that occurs in practise.

It is thus likely that the predictions of equilibrium theories are conservative in some, but not all, cases.

4.7 Assessment of flood levels

A number of the scour equations discussed above, for example, in Sections 4.1, 4.2 and 4.3, predict a depth of flow within the constricted section. To determine the level of the scoured depth it is necessary to determine the water level during the flood. This aspect seems to be little discussed. In many cases it seems to be implicitly assumed that the water level to be used should be the water level one would calculate in the unscoured condition. This will over-estimate the water level and hence lead to a predicted bed level that is higher then the true scoured bed level. Little work seems to have been done on the impact of this so it is difficult to assess its impact.

4.7 Numerical modelling

Given the problems with the desk methods described above it seems natural to consider the application of numerical methods to the problems of estimating constriction scour. Meadowcroft (1991) showed that conventional one-dimensional, mobile bed river models could be used to assess constriction scour during a flood. Such a modelling approach overcomes a number of the problems associated with the methods discussed above. The water level should be assessed accurately during the flood and it is not necessary to make the assumption of a long contraction. The time development of the scour should also be taken into account. If the model can take into account the change in bed sediment composition then the impact of armouring could be included.

The use of a one-dimensional model does not, however, remove all the problems. Such models use a sediment transport equation to determine the sediment transport rate at each cross-section. The accuracy of the predictions depends upon the accuracy of this transport equation. In cases where the scour is significant this may lead to bed slopes which are significantly different from the water surface slope. In these cases it may be necessary to take this into account in predicting the sediment transport rate (Kovacs and Parker, 1994). The extent of the model upstream of the constriction should be long enough so that the predictions at the constriction are not influenced by the upstream boundary conditions, particularly the upstream sediment load.

In Section 4.1, it was pointed out the results of Keller suggested that scour depths at rapid constrictions could be influenced by the contraction of the flow and the development of a vena contracta. This effect cannot be simulated by a one-dimensional model and so for rapid contractions it may be necessary to use either two or three dimensional numerical models.

5 Conclusions

Methods for predicting constriction scour by modelling the problem as scour at a long contraction may underestimate the scour that takes place at a rapid, short constriction. By assuming that a vena contracta is developed at the constricted section it may be able to improve the scour predictions.

The regime approach proposed by Blench is fundamentally flawed and may not give accurate predictions of scour.

The methods proposed to take account of the impact of armouring assume that a proportion of the bed material is stable. This ignores cases where all or most of the sediment is moving but the bed is armoured.

Numerical model tests suggest that in many cases the time scale to develop equilibrium scour is significantly longer than the duration of a flood event. This implies that equilibrium scour equations may overestimate the depth of scour.

A number of methods of estimating constriction scour are based on estimating a depth of flow. To apply such methods a water level is needed to determine the scoured bed level. This problem has not been adequately discussed in the past.

Many of the problems of the desk methods for estimating constriction scour can be overcome by the application of numerical models. The problem with flow separation in short, rapid contractions suggests that one-dimensional models will not adequately reproduce scour under these circumstances and that two or three dimensional models may be required.

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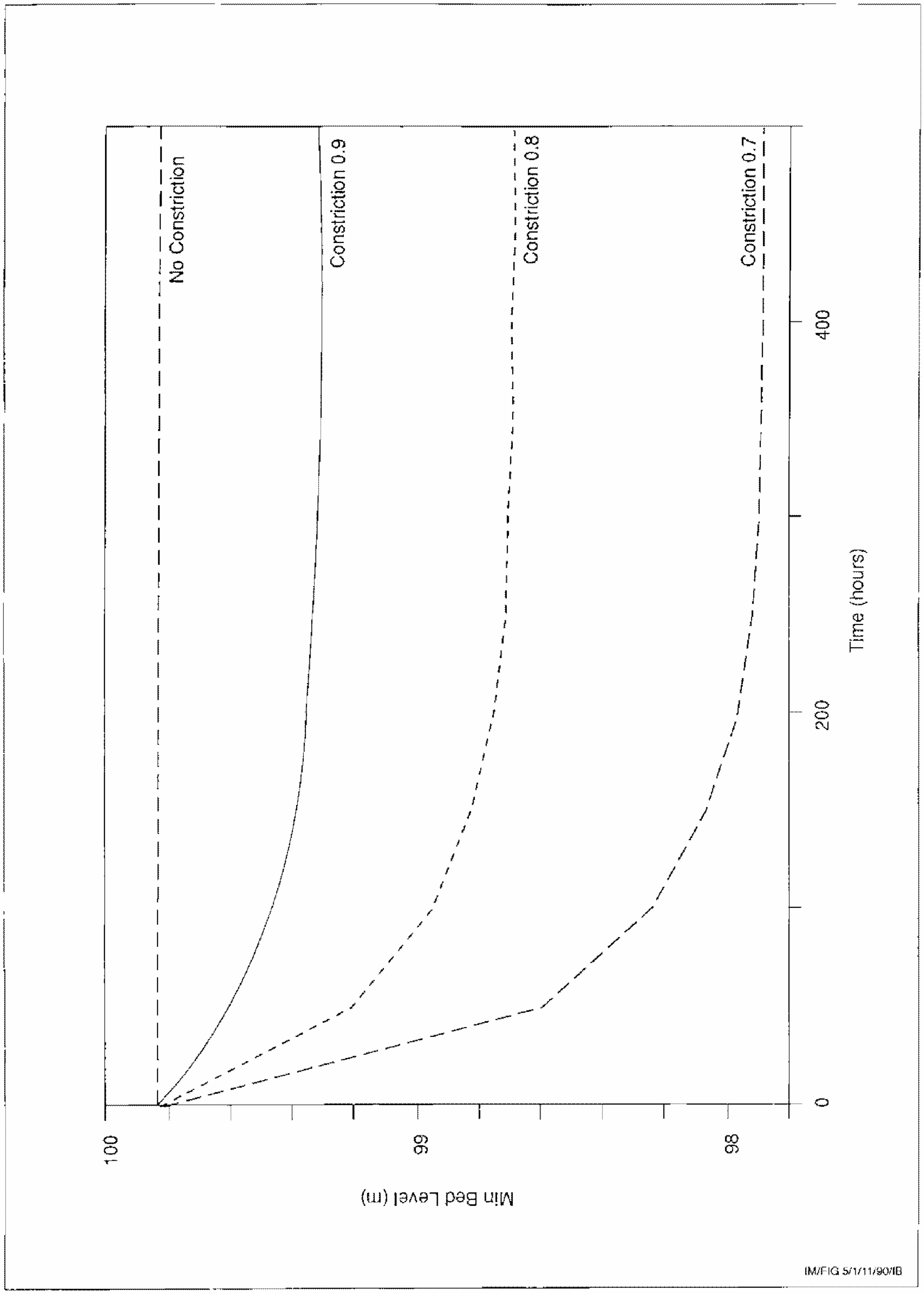

Fig 1 Minimum bed level in constricted reach: effect of different channel constrictions: Series 1

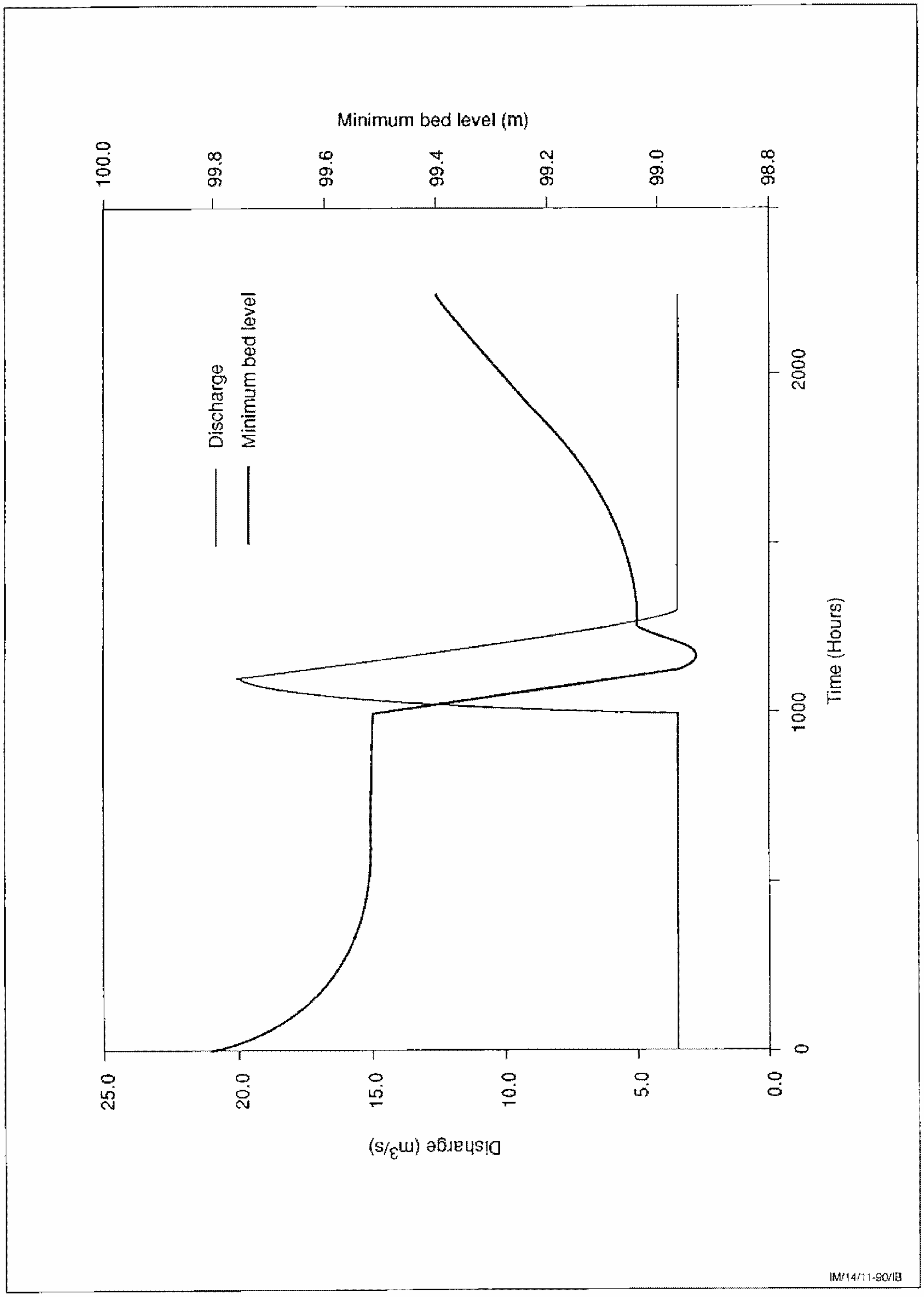

Fig 2 **300 hour flood hydrograph: Variation of minimum general scoured bed level with time, numerical model results**

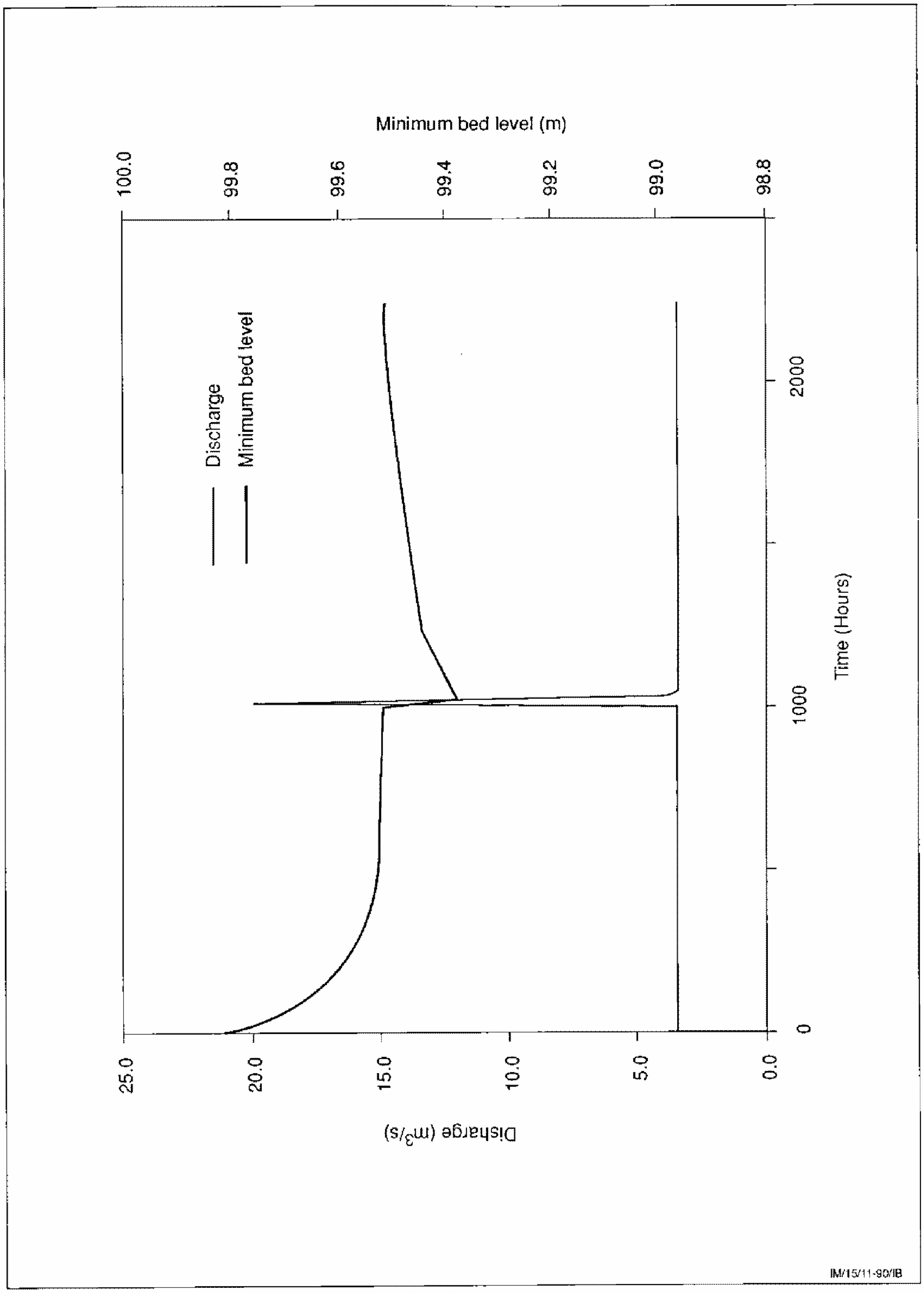

Fig 3 30 hour flood hydrograph: Variation of minimum general scoured bed level with time