WORKING PAPER 421

A LABORATORY STUDY OF THE MECHANISMS OF BACTERIAL WASH-OUT FROM THE STREAM BOTTOM SEDIMENT STORE

ALAN JENKINS* AND ADRIAN McDONALD**

* Stirling University

** School of Geography
University of Leeds
Leeds LS2 9JT

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ABSTRACT

The process of bacterial entrainment from the stream bottom sediment store is investigated using a laboratory flume. FC concentrations are determined from water samples taken at increasing bed velocities and indicate a log log relationship. The implications of this relationship with respect to the assumption of a critical threshold velocity for entrainment, as described in a previous modelling study, are discussed. The results emphasise that bacterial movement from a sedimentary store, in response to increased flow velocity, does occur although serious limitations exist when attempting to apply the empirical data from the flume to the field situation. In the light of the results, the interaction between settlement and wash-out processes are discussed.

LIST OF FIGURES AND TABLES

INTRODUCTION

In upland oligotrophic streams the fecal bacterial population in the water responds to increased discharge producing marked increases in concentration. This phenomena is well documented and has been reported in a variety of different stream environments (Teller, 1963; Kunkle and Meiman, 1967; Feachem, 1974; McSwain and Swank, 1977; McDonald and Kay, 1981). The implication of these studies is that a store of fecal bacteria exists within the catchment and contributes organisms to the stream water during storm periods. Three possible locations of such a store have been suggested; the catchment soil (Evans and Owens, 1972), the catchment land surface (Morrison and Fair, 1966) and the stream bottom sediment (Kunkle, 1970; Matson *et al.*, 1978). In all three cases, contribution of bacteria to the stream water would be induced by the increased discharge itself or by the hydrological processes which operate in the catchment to produce the increased flow.

In an effort to identify the immediate source area of bacteria contributing to high flow events, McDonald, Kay and Jenkins (1983) reported the results of a series of artificial hydrographs on the R. Washburn, N. Yorks. Water was released from Thruscross reservoir during rain-free periods. These induced storm hydrographs demonstrated peak bacterial concentrations of magnitude and timing comparable with the observed bacterial response to natural "rainfall induced" hydrographs on the same river. The conclusion that a bacterial store exists in the stream bottom sediment is inescapable because advection of bacteria from soil and surface sites occurred at a low and unchanged rate throughout the duration of the event. It is, therefore, assumed that bacteria in the sediment will be entrained as a direct result of the increased erosive power of the stream as discharge increases, or possibly by periodic sediment release following cobble movement (Jenkins *et al.*, 1984).

The existence and viability of a sedimentary store of bacteria gave rise to the deterministic process-based approach to modelling stream water bacterial concentrations described by Jenkins *et al.*, (1984). The essence of the proposed model is that the concentration of organisms in the water are the result of the interaction between input from the surrounding catchment, settlement into the sediment, wash-out from the sediment and die-off. Each of these processes are described in terms of stream discharge because this paramater represents the main control on transport and store size. Die-off is assumed to exhibit exponential decay in proportion to the numbers of bacteria present.

The wash-out mechanism, because of the association of bacteria with sediment particles, is assumed to be described by a sediment transport function which utilises a critical velocity, or threshold, for movement. This assumption clearly requires qualification as the entrainment of bacteria has been shown to be of prime importance in producing bacterial peaks during storm periods.

METHODS AND MATERIALS

Field studies of wash-out of bacteria from bottom sediment sites into the water column are unlikely to yield information describing the mechanism and rate of entrainment for three reasons. Firstly, bed velocity cannot be controlled to a suitable level of accuracy. Secondly, the concentration of bacteria in stream water is influenced by factors other than entrainment, notably input from surface and subsurface sources and the influence of die-off. Lastly, river water bacterial concentrations have been found to be extremely variable even under baseflow conditions (McDonald and Kay, 1981).

Given these problems the study reported here was undertaken in the laboratory and utilised a shallow-bed Ahlborn tank, as shown in Figure 1. This was thoroughly cleaned, disinfected and rinsed with distilled water before each experimental run and subsequently filled with a further 600 litres of distilled water. Flow was controlled via a manually-operated diaphragm valve situated on the flume return flow pipe (see Figure 1). This was opened at regular intervals until maximum flow was reached and then closed at the same intervals to reach zero flow.

Bed velocity was measured after each experiment using a CID electromagnetic flow meter. To facilitate this, a regular sampling grid was established at 10 cm intervals over the area of simulated river bed and bed velocity measurements were taken at alternate valve settings. Mean velocity and (90%) peak velocity were then averaged for each flow level, as demonstrated in Figure 2.

Stones for the laboratory simulation of river bed processes were collected from the bed of the R. Washburn, in sterile polythene bags. These were transported to the laboratory and carefully introduced into the flume at zero flow. Time elapsed between stone collection from the river sites and initial incubation of the water samples recovered from the flume during the experiment, never exceeded the six-hour time constraint suggested by DHSS (1982). Collection of sediment and bacteria from the stone surfaces and flume bed was achieved by employing a simple suction device which removed, without loss, the fine layer of bacteria and sediment at the water interface. During the experiment water samples were collected in sterile 500 ml glass-stoppered bottles.

The indicator organisms selected for the study were Fecal Coliforms (FC) and *Escherichia coli* (EC). These were used because of their widespread acceptance as major indicator species. FC was enumerated by the membrane filtration technique using an FC media (APHA, 1975) and EC by the multiple tube fermentation technique using minerals modified glutamate media (DHSS, 1982). The former method was utilised for water samples and the latter for sediment samples because of the problems encountered with samples of high sediment content in blocking the filter membrane (Geldreich, 1968). The two organisms may be equated on the basis that 96.8% of FC have been found to be EC organisms (Dufour, 1977).

RESULTS AND DISCUSSION

The results of the four experiments undertaken all demonstrate increasing concentration of bacteria in the water as velocity is increased above zero. The relationship between bed velocity and FC concentration in the water is not linear, but is best described as a log log function of the form

$$C = aV^b$$

where C = concentration of FC in the water ($.100\ ml^{-1}$)
V = bed velocity ($cm\ sec^{-1}$)
a & b = regression constants

Figures 3 to 6 show this relationship for the four runs together with the calculated regression equations. Table 1 reports the data from an examination of the sediment on the stones and on the stream bed, during experiments 1 and 4, and clearly demonstrates two important points. Firstly, that the bacterial concentration on the river stones is not seriously depleted during transportation from the river to the flume. Secondly, and more importantly, areas of accumulated sediment on the flume bed produces high concentration of bacteria and show that movement of bacteria from one sediment site to another is occurring. The magnitude of the bacterial concentration at these re-deposited sites clearly indicates that wash-out is an important process in stream microbial dynamics.

The empirical log log relationship, discussed earlier, implies that the assumption of a critical threshold velocity for bacterial entrainment is questionable. This relationship, however, cannot be directly incorporated into a modelling strategy for three broad sets of reasons: (i) problems inherent in the use of "rating curves" to predict particle concentrations in the flow; (ii) the assumption of dynamic equilibrium of bacteria in terms of settlement and wash-out interaction; and (iii) a problem of scale with respect to flume and river conditions.

In terms of suspended sediment prediction, a field which clearly has parallels to this work, Walling (1978) discussed the application of the "rating curve" technique whereby a regression model is utilised to describe the sediment-discharge relationship in a stream. In this case the rating curve is an empirical model where no account is taken of processes producing observed concentrations in suspended sediment. Such empirical relationships should not, however, be used to predict sediment concentrations for larger or smaller flows than those observed in its construction, nor should it be applied to discharge sequences other than those of the period of observation (McCaig, 1981). This is particularly important when using empirical models to describe bacterial concentrations as the variables and inputs to the system are not time invariant.

The second problem is a direct result of the absence of a definite relationship between settlement and velocity. That is, if settlement is not occurring at high velocities, it is possible that an 'active' layer of bacteria, of finite size, is being washed out of the sediment store and the size of the active layer is more important than bed velocity in determining bacterial concentrations in the water. The situation shown in Figure 7 illustrates a situation whereby the active layer of bacteria may be entirely removed irrespective of the level of bed velocity. Rate of entrainment, however, may be dependent on bed velocity with the available store being washed out more quickly at high velocities than at low velocities. Clearly this process could account for the observed situation in the flume. Two further possibilities exist whereby the observed flume results may be explained in terms of active layer depletion. In the first case, shown in Figure 8, rate of wash-out of bacteria is constant through time at all bed velocities. Peak bacterial concentration, or saturation level, may then be dictated by bed velocity if it is assumed that a greater proportion of the active layer becomes available at increasing bed velocity. Secondly, assuming that wash-out occurs at a faster rate with higher bed velocities and again, that all of the active layer is only available for entrainment at maximum velocity, the situation shown in Figure 9 will occur. Clearly, the results of this study are of limited use in distinguishing between a process of active layer depletion or the dynamic equilibrium involving settlement and wash-out assumed in the process-based model (Jenkins *et al.*, 1984).

Finally, the problem of scale relates to the "similarity" between the flume channel and the natural channel. Richards (1982) states that flow conditions in laboratory flume studies should, as near as possible, reproduce the turbulence intensity (i.e. Reynolds Number and Froude Number) of natural streams, as these indices are dimensionless and independent of the scale to which they are applied. In this respect, both flume and river exhibit subcritical flow (i.e. $F_r < 1$), although very low Reynolds Numbers were found in the flume at low velocities which may be interpreted as falling within the 'transitional' zone between laminar and turbulent flow (i.e. R_e 500-2000) as demonstrated in Figure 10.

CONCLUSIONS

The assumption that the process of bacterial entrainment from the stream bottom sediment store is described by a suspended sediment function is supported by the results of this study. Bacteria have been found to move in association with the sediment, and the empirical relationship between bacteria in the flow and bed velocity shows broad similarities with sediment rating curves. The assumption of a critical threshold velocity for initiation of movement is, however, questionable as wash-out has been found to occur at all levels of bed velocity. It must be noted, however, that serious problems of scale may exist when attempting to apply the observed flume results to the natural river environment. It is equally likely that a threshold for wash-out may exist in the R. Washburn at a velocity in excess of 23 cm sec^{-1}, the maximum flume velocity observed (this represents a discharge of approximately 1.2 $m^3.s^{-1}$, from Figure 11).

In the flume, the interaction between settlement and wash-out processes may be responsible for producing observed bacterial concentrations because die-off may be assumed to be negligible and input of bacteria is zero. At low velocities, therefore, entrainment of organisms takes place at a slow rate and settlement occurs such that the bacterial concentration in the water achieves equilibrium with bacterial numbers in the sediment and remains at a low level. As velocity increases, entrainment of sediment-bound organisms increases rapidly, settlement continues at its constant rate (or possibly lower) and, consequently, the concentration of bacteria in the water begins to rise to peak just before maximum velocity is reached. With falling velocity, addition of bacteria through wash-out remains higher than losses through settlement thereby maintaining high concentrations of bacteria in the water which decrease slowly. This pattern of change of bacterial concentration with increased and decreased velocity in the flume (i.e. the passage of a storm hydrograph) presents similarities with observed change of bacterial concentration through both natural and artificial hydrographs (Davis *et al.*, 1977; McDonald and Kay, 1981; McDonald, Kay and Jenkins, 1982). Given limitations of scale it is proposed, therefore, that the scenario outlined here may be broadly applied to the river environment with die-off and input parameters superimposed.

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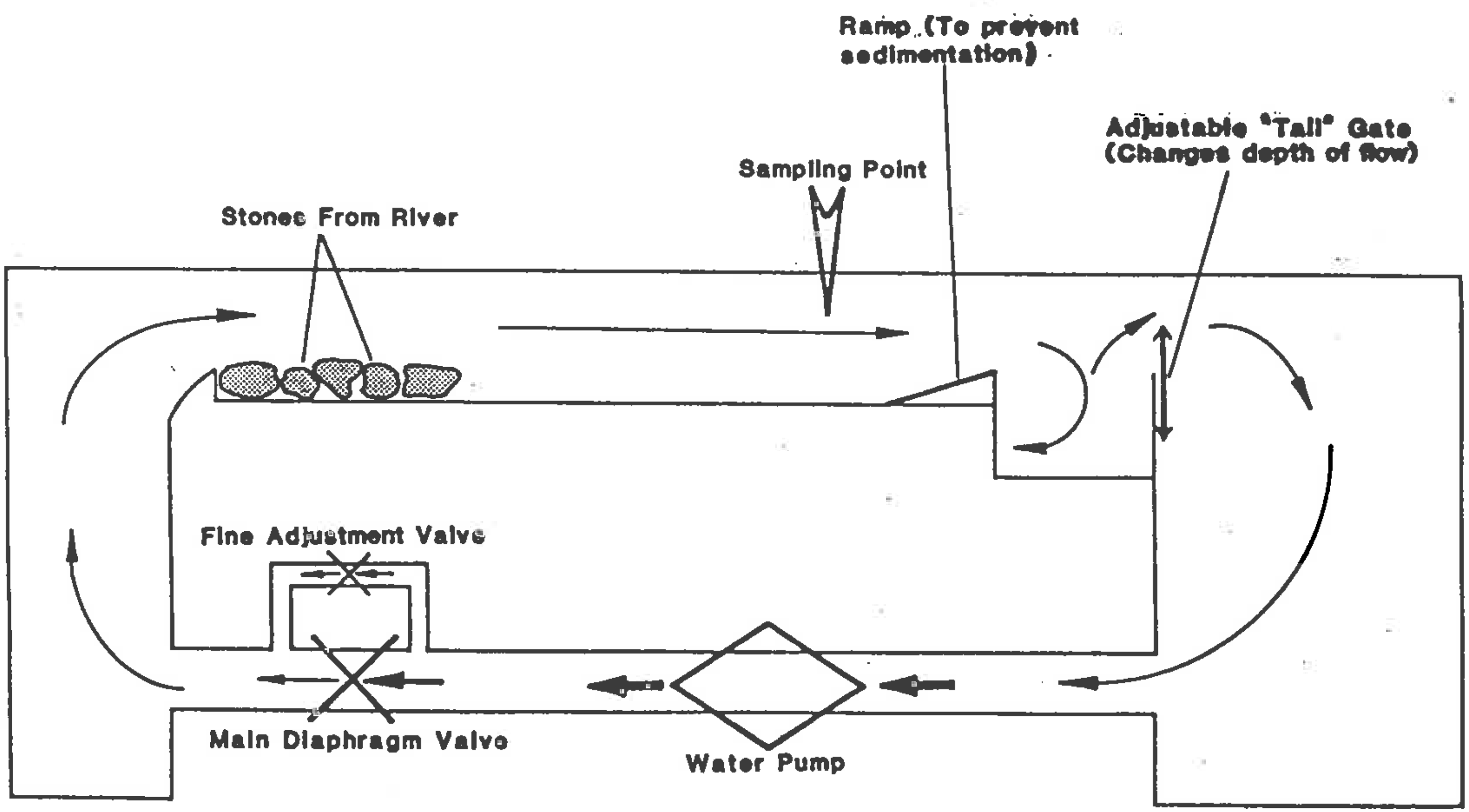

FIGURE 1. A DIAGRAMMATIC REPRESENTATION OF THE AHLBORN TANK USED IN THE WASH-OUT EXPERIMENTS

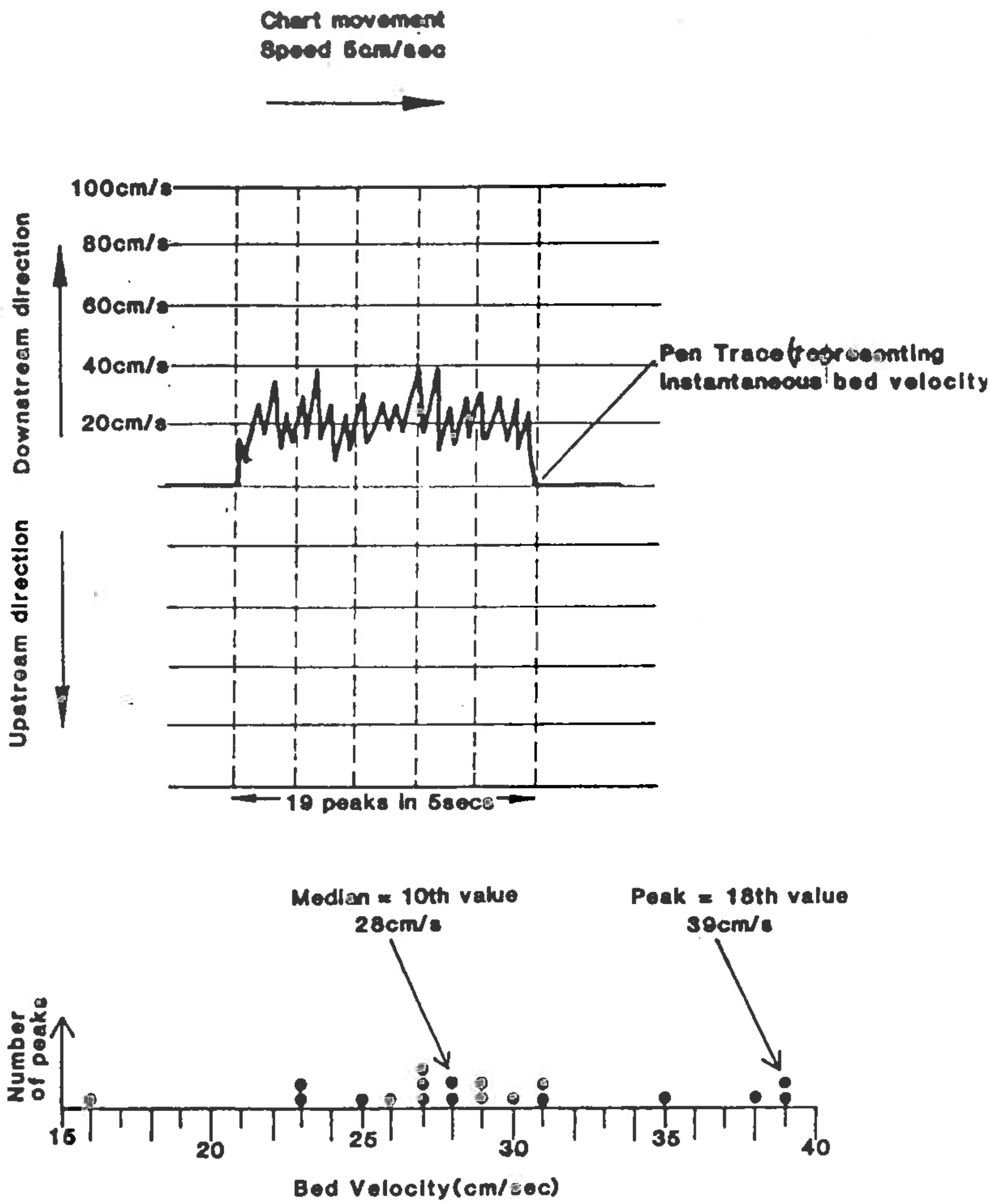

FIGURE 2. AN EXAMPLE OF CHART OUTPUT FOR THE CID ELECTRO-MAGNETIC FLOW METER SYSTEM. THE METHOD OF CALCULATION OF PEAK AND MEDIAN BED VELOCITY IS ILLUSTRATED

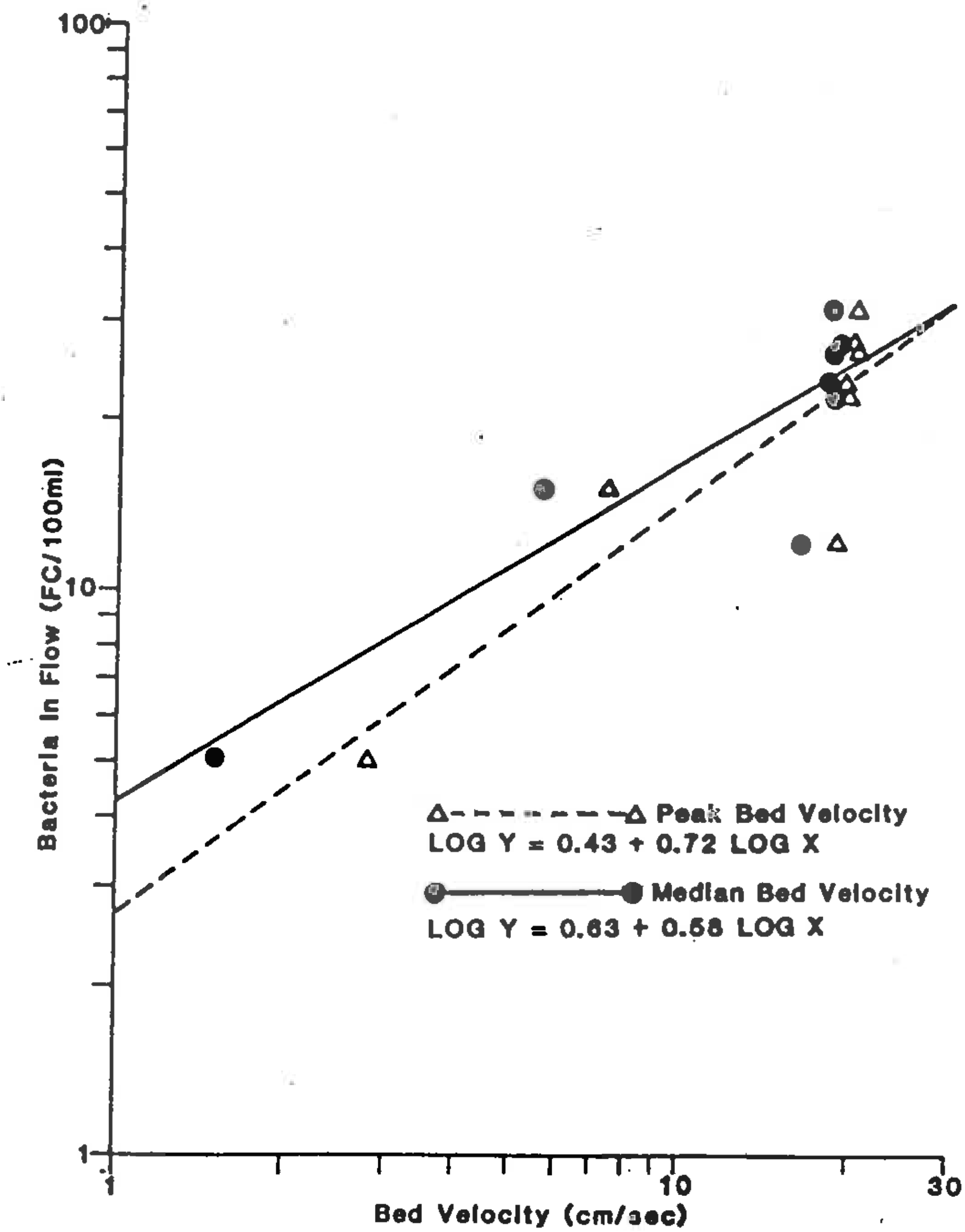

FIGURE 3. THE RELATIONSHIP BETWEEN FC IN THE FLOW AND PEAK AND MEDIAN BED VELOCITY DURING FLUME RUN 1

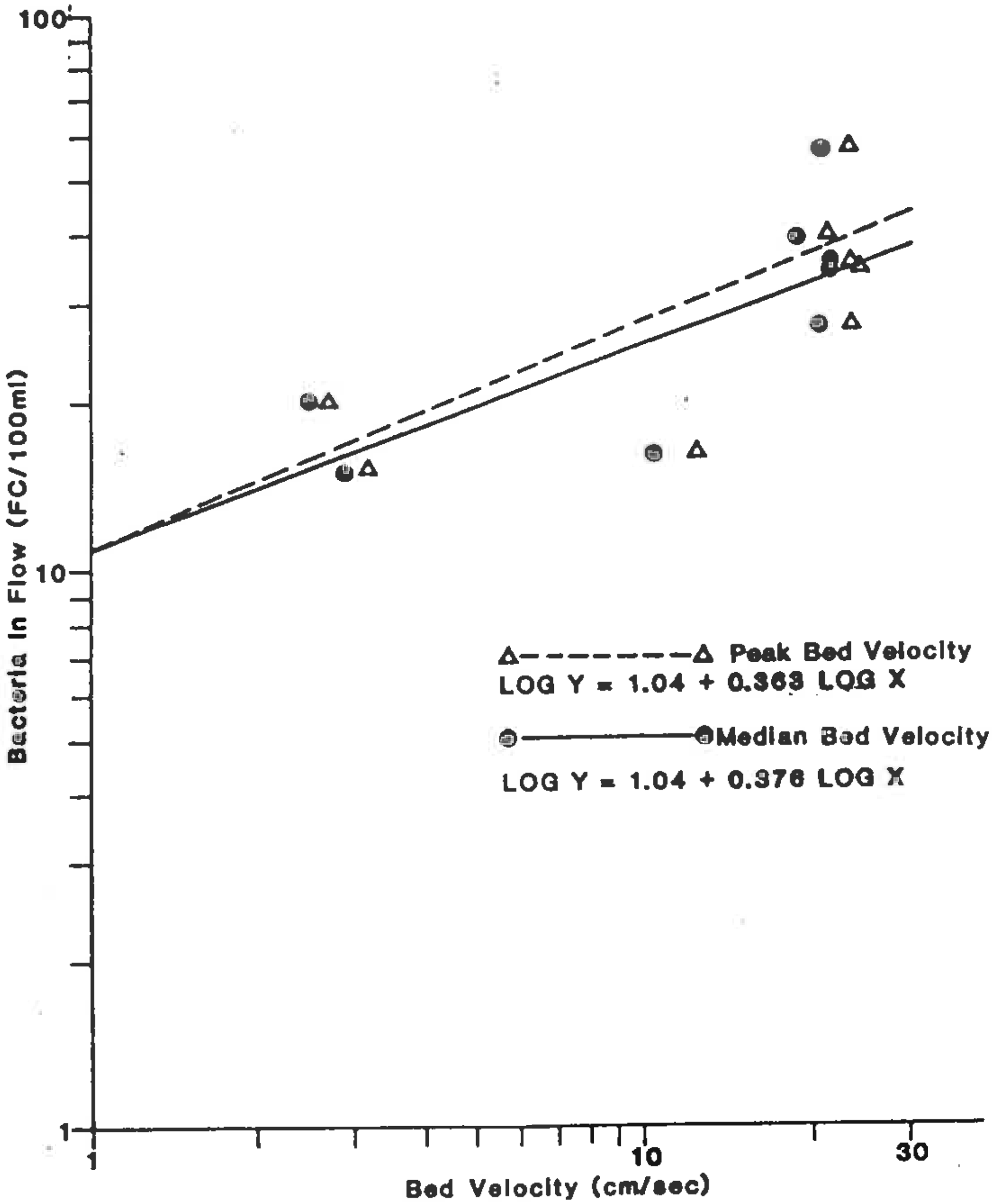

FIGURE 4. THE RELATIONSHIP BETWEEN FC IN THE FLOW AND PEAK AND MEDIAN BED VELOCITY DURING FLUME RUN 2

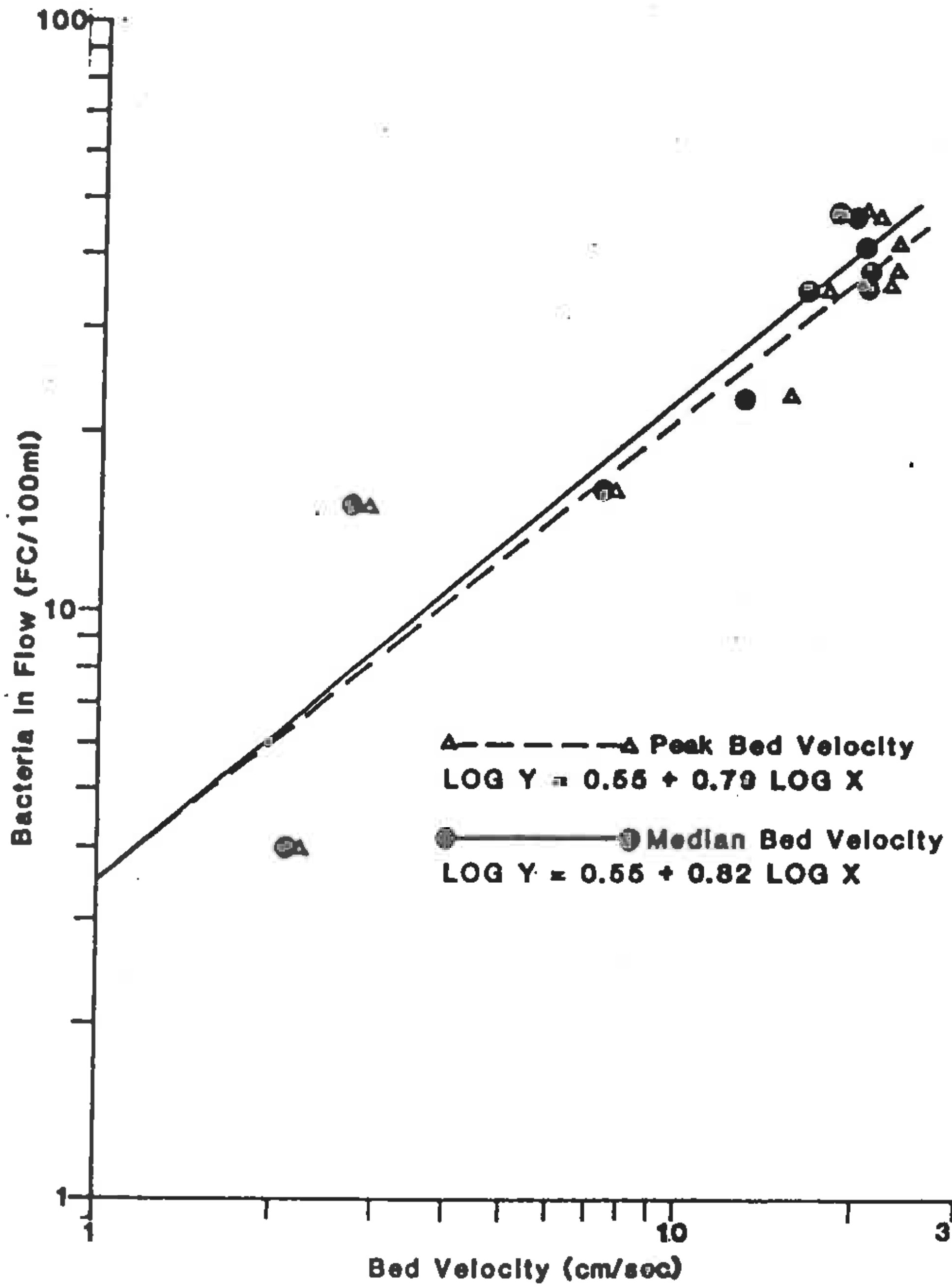

FIGURE 5. THE RELATIONSHIP BETWEEN FC IN THE FLOW AND PEAK AND MEDIAN BED VELOCITY DURING FLUME RUN 3

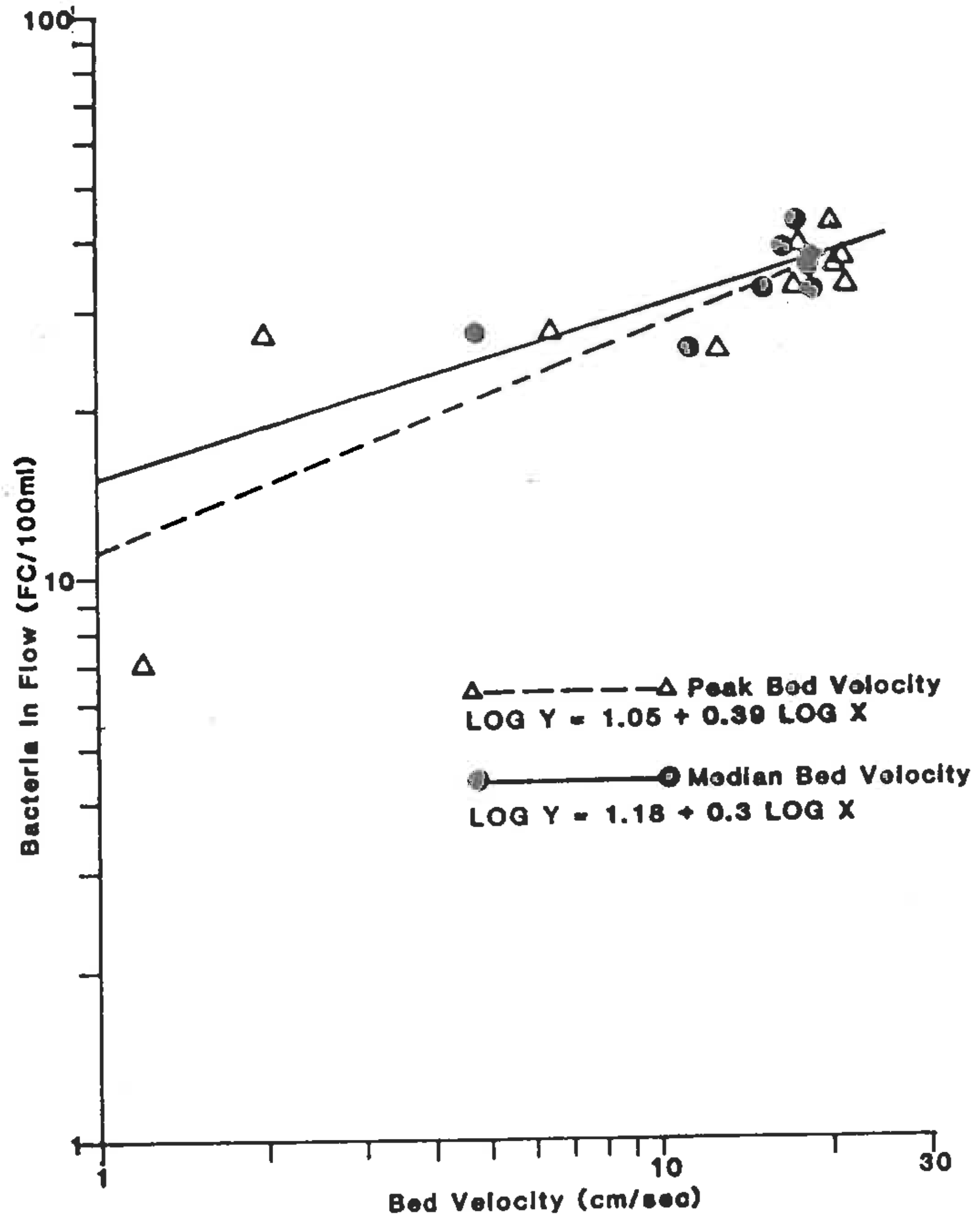

FIGURE 6. THE RELATIONSHIP BETWEEN FC IN THE FLOW AND PEAK AND MEDIAN BED VELOCITY DURING FLUME RUN 4

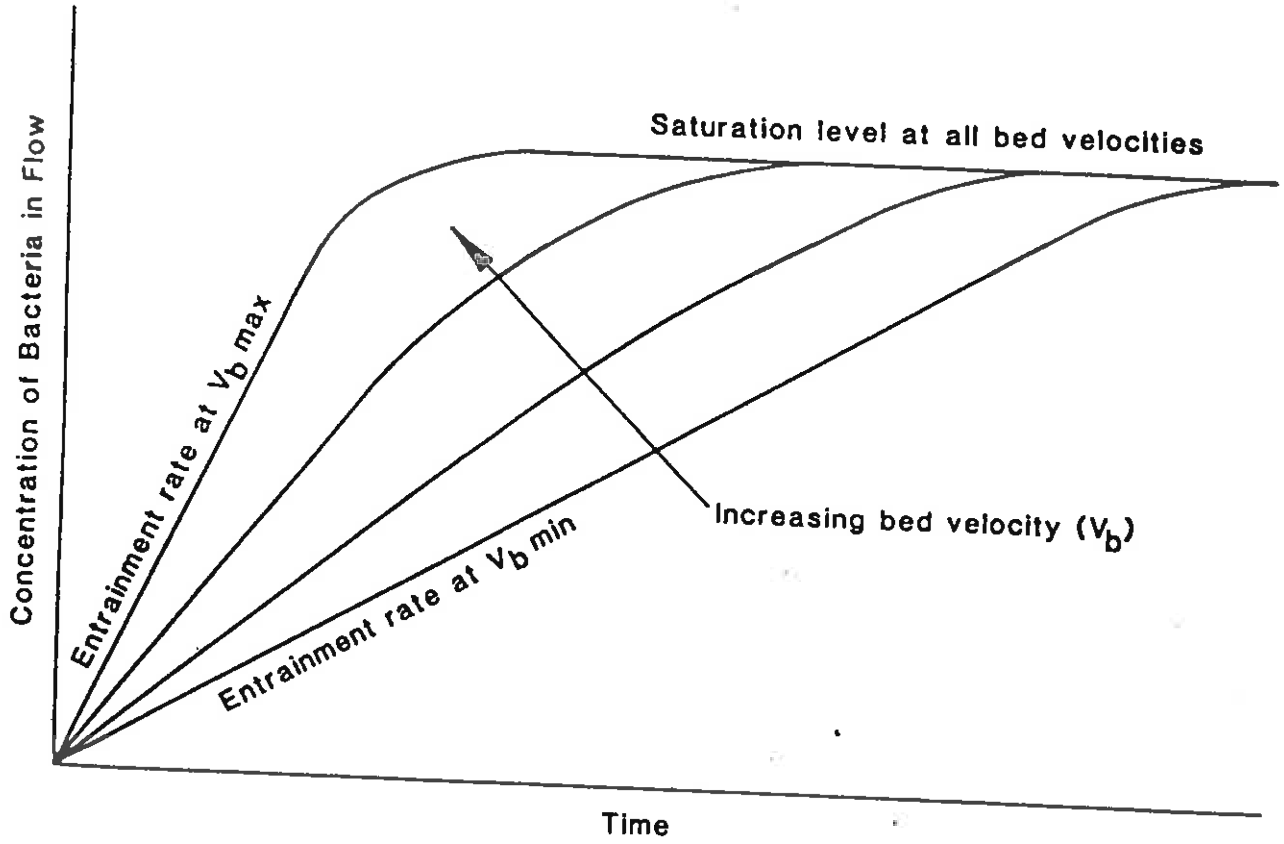

FIGURE 7. THE RESULT OF 'ACTIVE' LAYER DEPLETION THROUGH TIME WHEN ALL OF THE LAYER IS AVAILABLE AT ALL BED VELOCITIES. RATE OF ENTRAINMENT IS SLOWER AT LOW BED VELOCITIES

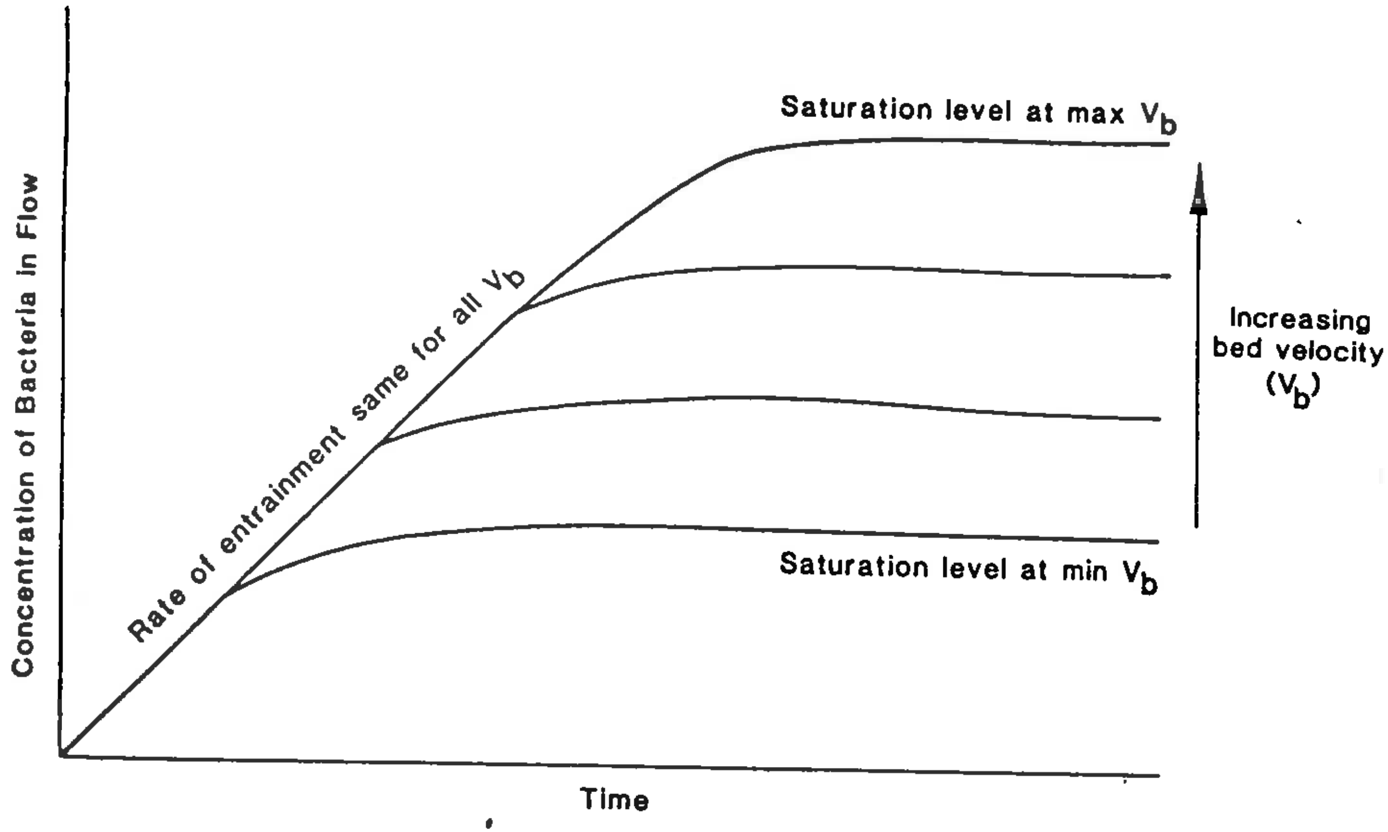

FIGURE 8. THE RESULT OF 'ACTIVE' LAYER DEPLETION THROUGH TIME WHEN ALL OF THE LAYER IS AVAILABLE ONLY TO THE HIGHEST BED VELOCITY. RATE OF ENTRAINMENT IS CONSTANT AT ALL LOW BED VELOCITIES

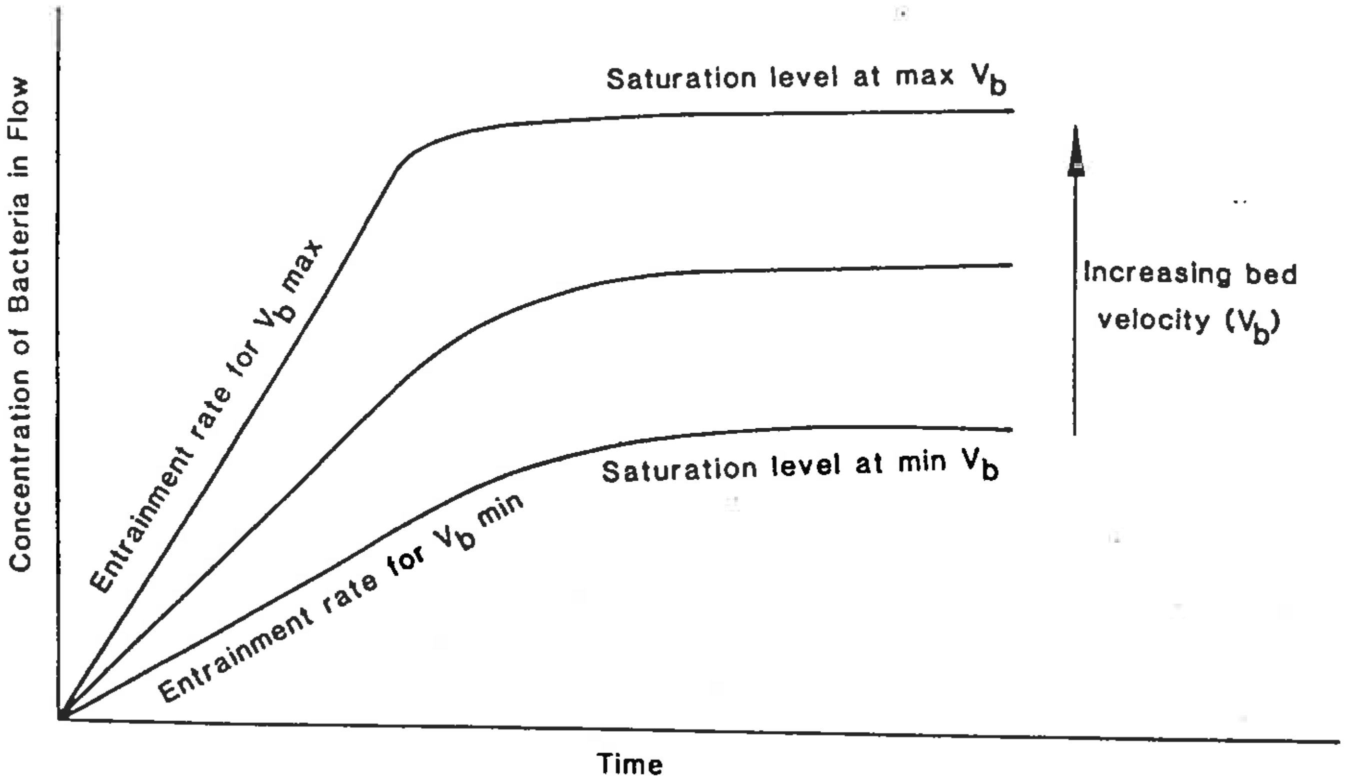

FIGURE 9. THE RESULT OF 'ACTIVE' LAYER DEPLETION THROUGH TIME WHEN ALL OF THE LAYER IS AVAILABLE ONLY TO THE HIGHEST BED VELOCITY. RATE OF ENTRAINMENT IS LOWER FOR LOW BED VELOCITIES

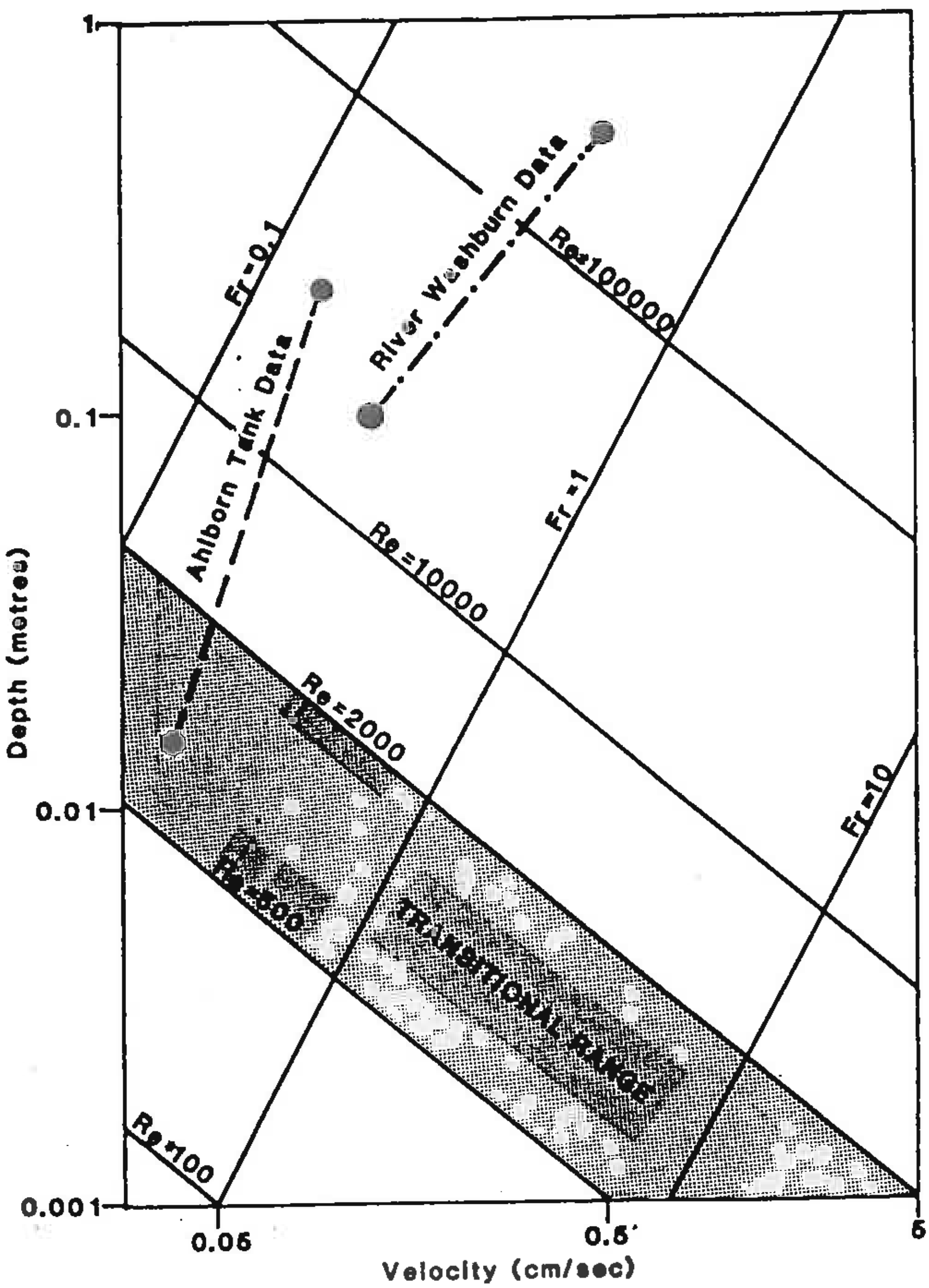

FIGURE 10. COMPARISON OF THE FLOW CONDITIONS, WITH RESPECT TO TURBULENCE INTENSITY, IN THE FLUME AND THE R. WASHBURN

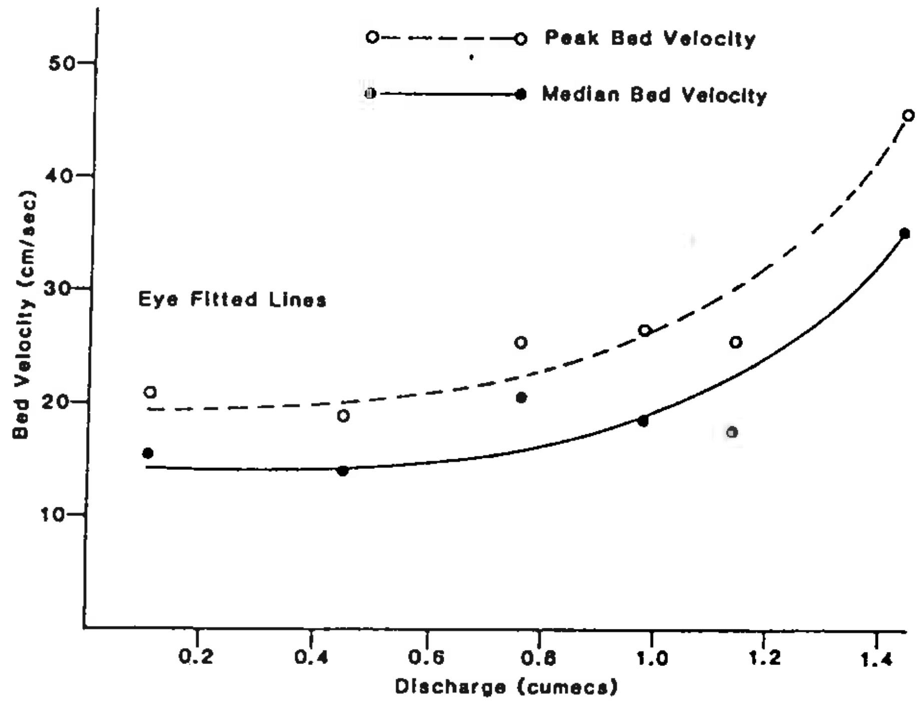

FIGURE 11. THE RELATIONSHIP BETWEEN DISCHARGE AND MEDIAN AND PEAK BED VELOCITY IN THE R. WASHBURN

TABLE 1. BACTERIAL CONCENTRATION AT DIFFERENT BED SITES:

(i) from store surfaces *in situ*;
(ii) from store surfaces in the flume;
(iii) from store surfaces in the flume after a run;
(iv) from areas of sediment accumulation in the flume.

	EXPERIMENTAL RUN 1 F.C./ cm2	EXPERIMENTAL RUN 2 F.C./ cm2
F.C. Concentrations On River Stones.	4500+ 4500+ 4500+ MEAN=4500+	2250 2250 4000 MEAN = 2833
F.C. Concentrations On Stones In Flume Before Run.	4500+ 4500+ MEAN=4500+	1250 6875 2750 MEAN = 3625
F.C. Concentrations On Stones In Flume After Run.	4500+ 4500+ MEAN=4500+	2000 1125 4250 MEAN = 2458
F.C. Concentrations From Areas Of Bed Sediment Accumulation After Run.	1375 875 2250 MEAN=1500	875 1375 425 MEAN = 892