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DEVELOPMENT OF A CALIBRATION STRATEGY FOR SUSPENDED SEDIMENT SAMPLERS - PHASE I

by

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MANAGEMENT PERSPECTIVE

Suspended sediment is the dominant component of the total sediment load transported by alluvial streams. Accurate measurement of suspended-sediment concentration is important for application in a wide range of engineering and environmental problems. Recent emphasis on considering fine sediment fractions as a water quality parameter, make accurate sediment sampling more important than ever. The Water Survey of Canada uses about 600 suspended-sediment samplers in its national program. Their calibration requires significant time and resources. The establishment of a sampler calibration strategy by the Water Survey of Canada and the National Water Research Institute is a necessary step forward in better management of Canada's water resources.

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ABSTRACT

Using dimensional analysis, basic equations were developed as a basis to formulate a suspended-sediment sampler calibration strategy. The equations were applied to review the calibration method used by the Water Survey of Canada prior to 1972. A research program is proposed to provide the necessary information to establish an updated calibration strategy.

PERSPECTIVE-GESTION

Dans les cours d'eau qui charrient des alluvions, les sédiments en suspension constituent la composante principale de la charge sédimentaire totale. Il s'avère important, pour résoudre une grande variété de problèmes relatifs à l'environnement et aux travaux d'ingénierie, de mesurer avec précision la concentratioin des sédiments en suspension. Comme les sédiments fins sont depuis peu considérés comme un paramètre important de la qualité de l'eau, il est aujourd'hui plus que jamais nécessaire d'obtenir des mesures précises relatives à ces sédiments. La Division des relevés hydrologiques du Canada utilise, dans le cadre de son programme national, environ 600 appareils d'échantillonnage de sédiments en suspension. Beaucoup de temps et de ressources sont consacrés à l'étalonnage de ces appareils. L'établissement d'une stratégie d'étalonnage de ces appareils d'échantillonnage par la Division des relevés hydrologiques du Canada et l'Institut national de recherche sur les eaux est une étape nécessaire pour améliorer la gestion des ressources en eau du Canada.

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RÉSUMÉ

Des équations de base ont été créées à l'aide de l'analyse dimensionnelle pour mettre au point une stratégie d'étalonnage des appareils d'échantillonnage de sédiments en suspension. Ces équations ont été utilisées pour réviser les méthodes d'étalonnage employées par la Division des relevés hydrologiques du Canada avant 1972. Un programme de recherche visant à fournir les informations nécessaires à l'établissement d'une stratégie d'étalonnage modernisée est proposé.

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1.0 INTRODUCTION

The collection, computation and publication of fluvial sediment and related data are a national program managed by the Water Survey of Canada (WSC). The data are used to evaluate the effects of sedimentation on the life and economics of projects related to water supply, pollution, navigation, flood control and recreation. The fine fractions of the suspended sediment load are known to be carriers of toxic substances and therefore suspended-sediment concentrations are an important indicator of water quality in rivers.

The accuracy and calibration of all suspended-sediment samplers must be checked to ensure that reliable data are obtained because the cost of field measurement is very high and the determination of water quality is becoming increasingly important. Prior to 1972, suspended-sediment sampler calibrations were conducted by WSC at its towing tank facility in Calgary, Alberta. At the present time, WSC is in the process of developing a quality control system for its data gathering activities and wishes to re-define its sampler calibration program. The Hydraulics Laboratory of the National Water Research Institute (NWRI), was asked to participate in the review of the existing calibration methodology and the development of a calibration strategy commensurate with present accuracy requirements. Once a stragtegy is in place, the calibration of the samplers will be conducted in the towing tank of the Hydraulics Laboratory at NWRI.

This report represents the first phase of the development of the required sampler calibration strategy. The work was conducted jointly by the Sediment Section of WSC, HQ, in Ottawa and the Research and Development Branch at NWRI, at Burlington, Ontario.

2.0 FORMULATION OF GENERAL CALIBRATION EQUATION

The purpose of the suspended-sediment sampler is to obtain a sample that is representative of the water-sediment mixture moving in the stream in the vicinity of the sampler. In general, the samplers have been designed for iso-kinetic sampling in which the stream velocity at the point of sampling is equal to the velocity of flow through the sampler nozzle. It is assumed that the flow entering through the nozzle contains the same water-sediment mixture as the streamflow being sampled. The details of several of the samplers used in the WSC program are described by Guy and Norman (1970).

All of the earlier models of suspended-sediment samplers in use operate on the same principle. When the sampler is submerged with the nozzle pointed directly into the flow, a part of the streamflow enters the sampler container through the nozzle as air is exhausted under the combined effect of three forces:

1. The dynamic positive head of the flow at the nozzle entrance.
2. A negative head at the air outlet port.
3. A hydrostatic pressure because of the difference in elevation between the nozzle entrance and the air outlet port.

During the sampling, a volume of the water-sediment mixture is collected in the sampler over a measured interval of time and from this, the flow rate into the sampler is computed. The velocity of the flow through the nozzle is then computed by dividing the flow rate by the cross-sectional area of the nozzle hole. This velocity, say, U_s, should be equal to the external streamflow velocity, say U_e, to ensure that the sampling is iso-kinetic so that the sediment flux in the streamflow, at the sampler position, can be computed as the product of the sediment concentration of the collected sample and the nozzle velocity U_s.

The relationship between U_s and U_e can be expressed as:

$$K = U_s/U_e \tag{1}$$

where K is a coefficient which must have a value close to 1.0 in order to ensure iso-kinetic sampling. The value of K for a given sampler is obtained from tests in a towing tank. In the effort to obtain good sampler performance, it is important to recognize that U_s can be expected to depend on a number of independent variables which must be identified and their importance determined. In general, the nozzle velocity U_s can be expected to depend on the variables expressed in the following functional relationship:

$$U_s = f(U_e, d_i, d_o, a, r, \theta, \sqrt{U'^2}, C, D_{50}, \psi, \rho, \nu, \text{sampler type}) \tag{2}$$

where f denotes a function, for a specific type of nozzle surface texture (i.e., brass, plastic, etc.); d_o = the outside diameter of the nozzle, d_i = the inside diameter of the nozzle, a = the length of nozzle extending from the nose of the sampler, r = the radius of curvature of the nose of the nozzle, θ = the angle of the axis of the nozzle with the horizontal, $\sqrt{U'^2}$ = the turbulence as root mean square of turbulence velocity fluctuations, C = the concentration of suspended sediment, D_{50} = median diameter of the suspended sediment, ψ = the grainsize distribution factor, ρ = the density of the water, ν = the kinematic viscosity of the water. The geometric parameters are shown schematically in Figure 1. Using dimensional analysis, one obtains for a given sampler type, the dimensionless relationship:

$$\frac{U_s}{U_e} = f_s\left(\frac{d_o}{d_i}, \frac{a}{d_i}, \frac{r}{d_i}, \theta, \frac{\sqrt{U'^2}}{U_e}, C, \frac{D_{50}}{d_i}, \psi, \frac{U_e d_i}{\nu}\right) \tag{3}$$

where f_s denotes a function for a specific type of sampler and nozzle material. For a given sampler, the variables r/d_i, d_o/d_i and a/d_i are specified and their effects are implicit in the calibration. Therefore they may be removed from equation (3). After some re-arranging the calibration equation may be expressed in the form

$$K = f_{s1}\left(\theta , \frac{\sqrt{U'^2}}{U_s} , C , \frac{D_{50}}{d_i} , \psi , \frac{U_s d_i}{\nu}\right) \qquad (4)$$

where f_{s1} denotes a function for the restrictions specified. Equation (4) represents the general calibration equation for a given sampler equipped with prefabricated nozzles of specified dimensions and surface roughness. This equation provides the basis for the development of a strategy for the calibration of the different types of suspended-sediment samplers used by the Water Survey of Canada.

3.0 METHOD OF CALIBRATION USED BY WSC

The method used by WSC consisted of two parts: a) calibration of the sampler with a given nozzle, and b) calibration of the nozzles.

3.1 Calibration of Sampler and Nozzle

In this part of the calibration, the sampler equipped with a particular nozzle was towed through a towing tank at a constant velocity, for a specified sampling time which depended on the towing velocity and was always equal to the time required to fill the sample bottle approximately 3/4 full. The volume of water collected was used to determine the nozzle velocity and this was plotted as a function of the towing velocity. This procedure was repeated for different towing velocities over the operating range of the sampler for the particular size of nozzle used. Different sizes of nozzles were used with the inside diameter increasing as the velocity decreased. This ensured that the sample volume was approximately the same for the same sampling time.

The procedure was repeated for each of the different sizes of nozzles used with each sampler. In all, three different sizes of nozzles (1/8", 3/16", 1/4") were used, each valid over a specified velocity range. Values of the nozzle velocity were plotted versus the corresponding towing carriage velocity as shown in Figure 2 which shows typical sampler calibrations for the three types of nozzles used (DeZeeuw and Chapman, 1971). Theoretically, proper (iso-kinetic) sampling requires that the velocity through the nozzle and the corresponding towing carriage velocity are equal. This is reflected by the "equal yield" line in Figure 2. WSC established tolerance limites of 10%. Any calibrations which fell within these limits was considered to be acceptable. However, the nozzles, because of their vulnerability, often became damaged and needed to be replaced. In order to avoid the time consuming task of recalibration with the sampler in the towing tank, an alternate method developed by DeZeeuw and Chapman (1971) was used to calibrate the nozzles.

3.2 Calibration of the Nozzles

The nozzles were calibrated independently of the sampler in a "bench-top" constant head tank. The nozzle was fastened to an adjustable pipe which passed through the bottom of the tank as shown schematically in Figure 3. The pipe served simultaneously as a nozzle mounting and outflow conduit. The tank was large enough and the nozzle was attached in such a way that there was no boundary interference on the flow at the nose of the nozzle. A nozzle was calibrated by fixing it so that the entrance of the nozzle was at a known elevation. The flow rate into the tank was then adjusted until a small overflow was obtained, resulting in a fixed water surface elevation in the test section. The difference between the water surface elevation and the nozzle entrance was then taken to be the head on the nozzle. At this point a volume of the outflow through the nozzle was measured over a period of time from which the nozzle velocity was computed. This procedure was repeated for different heads and flow rates until the expected operating range of the nozzle was covered. The results were then plotted in a format equivalent to nozzle velocity versus the head as shown in Figure 4.

To complete the calibration of a given sediment sampler, each of the nozzles used with the sampler was calibrated in the constant head tank after the calibration in the towing tank was completed. The data from the constant head tank calibrations were then plotted to provide a reference curve for each of the nozzles equivalent to that given in Figure 4. For each reference curve, the deviation of the sampler calibration from the iso-kinetic line was noted. If, for example, a sampler calibration with a given nozzle differed from the iso-kinetic line by, say, -8%, then the calibrations of any additional nozzles of the same size to be issued for the same sampler were considered to be satisfactory if they plotted slightly above the reference curve. This ensured that the performance of the sampler with the replacement nozzle was compatible with the original towing tank calibration.

3.3 Analysis of the WSC Method

The sampler calibration in the towing tank implicitly assumes that there is no significant effect due to the sediment concentration, grainsize of the sediment, grainsize distribution, and turbulence. Finally, before each calibration, care was taken that the sampler was properly aligned with the flow. Therefore equation (4) is reduced to the idealized form of

$$K = f_{s2}\left[\frac{U_s d_i}{\nu}\right] \qquad (5)$$

Equation (5) shows that for the towing tank calibrations, the value of K is a function only of the sampler Reynolds number, which represents the viscous effects of the water on the flow through the sampler from nozzle intake to the collection bottle. Although the fluid is always water, the Reynolds number is still important because the viscosity of the water changes significantly with water temperature (Rouse, 1965). The effects of temperature is not taken into account with the WSC method and need to be examined before a calibration procedure can be considered to be rigorous.

The form of equation (5) was examined using a typical data set for three different sizes of nozzles from WSC calibrations. Values of K and the Reynolds number and other pertinent information are given in Table 1. Values of K were plotted versus the Reynolds number as shown in Figure 5. The plot shows values of K varying about the ideal iso-kinetic value of 1.0 and this variability appears to be independent of the Reynolds number over the range tested. The values of K are well within the 10% error margins established as a goal by WSC. The data in Figure 5 represent different values of d_o/d_i and r/d_i, indicating that K is not too sensitive to these variables if their variation is small. This suggests that very close tolerances on the nozzle dimensions of d_i and r may not be necessary if an accuracy of 10% in the value of K is satisfactory. It is important that values of K should always be close to 1.0. It has been found that a deviation from iso-kinetic sampling (i.e., $K \neq 1.0$) causes errors in the sample concentration as shown in Figure 6 (Guy and Norman, 1970). When $K > 1.0$, oversampling occurs. For sediment sizes in the silt and clay range, the effect of grainsize and values of $K > 1.0$ is mild, resulting in errors of up to 10% when the grainsize is 0.062 mm and $K = 4.0$. However, as the particle sizes increase above 0.062 mm, the error in sediment concentration increases more rapidly as particle size increases for a given value of K and the rate of increase in the sampling error increases as K increases. When $K < 1.0$, undersampling occurs. For particle sizes less than about 0.062 mm, the effect of particle size and values of K is minor. When particle sizes become greater than 0.06 mm, the error in the sediment concentration increases significantly for a given value of K. It is also clear from Figure 6 that the effects of undersampling are not as severe as the effects of oversampling.

The calibration of the nozzles in the constant-head tank is equivalent to a comparison of the nozzle coefficients. For any fluid, the head required to pass a certain discharge through the nozzle is represented by the pressure drop which is a measure of the resistance to flow through the nozzle. The resistance is a function of the inside diameter of the nozzle, the length of the nozzle, the roughness of the flow passage in the nozzle, the radius of curvature of the nose of the nozzle, the velocity of the flow through the nozzle and the properties of the fluid. This can be expressed as

$$\Delta P = f_c(d_i, \ell, r, e, U_N, \rho, \nu) \tag{6}$$

where ΔP = the pressure drop between entrance and outlet of the nozzle, f_c = denotes a function, ℓ = the total length of the nozzle flow passage, r = the radius of curvature of the nozzle nose, e = the roughness of the nozzle flow passage, U_N = the average velocity of the flow in the nozzle, ρ = the density of the fluid and ν = the kinematic viscosity of the fluid. The geometric parameters are shown schematically in Figure 7. Using dimensional analysis one obtains

$$\frac{\Delta P}{\rho U_N^2} = f_{c^1}\left[\frac{\ell}{d_i}, \frac{r}{d_i}, \frac{e}{d_i}, \frac{U_N d_i}{\nu}\right] \tag{7}$$

where f_{c^1} denotes a function. A particular calibration is made for a nozzle of a particular size and type. Therefore, the variables ℓ/d_i, r/d_i and e/d_i are fixed and may be absorbed in the function. Therefore, equation (7) is reduced to

$$\frac{\Delta P}{\rho U_N^2} = f_{c^2}\left[\frac{U_N d_i}{\nu}\right] \tag{8}$$

where $f_c 2$ denotes a function. The function $f_c 2$ is the nozzle coefficient which may be denoted as C_N. The pressure drop can be converted to the equivalent head of water by the relationship

$$h = \frac{\Delta P}{\rho g} \tag{9}$$

where h is the equivalent head driving the flow through the nozzle and g = the acceleration due to gravity. Combining equations (8) and (9) results in

$$C_N = \frac{gh}{U_N^{\,2}} = f_c 2 \left[\frac{U_N d_i}{\nu} \right] \tag{10}$$

Equation (10) shows that for a given type of nozzle, the nozzle coefficient depends only on the nozzle Reynolds number. Data from constant-head tests conducted by WSC were used to compute values of the nozzle coefficients and the Reynolds number and these are given in Table 2. The results were plotted in Figure 8 as C_N versus $U_N d_i/\nu$ and smooth curves were drawn through the plotted points. Figure 8 shows that each nozzle has its own characteristic curve. The range of each curve is limited to the velocities over which the nozzle is used in practice. In all three cases the nozzle coefficient is dependent on the Reynolds number with the rate of dependence decreasing as the Reynolds number increases. It is quite clear from the shape of the curves that the nozzle coefficients tend toward independence of the Reynolds number as this increases and that this is dependent on the nozzle size and possibly other properties unique to each nozzle.

The values of C_N tend to be lower than one would expect and this is due to the fact that the effective head recorded during the WSC tests was taken to be the difference between the elevation of the water surface in the constant-head tank and the elevation of the nozzle intake. This is less than the real head driving the flow and thus accounts for the lower values of C_N. The fact that the nozzle coefficient depends on the Reynolds number is an indication that the nozzle coefficient may also be affected by changes in temperature because this affects the viscosity of the water. The WSC data in Table 2 do not include temperature measurements and therefore this effect cannot be assessed at this time. Considerations must be given to the effect of temperature if this method of testing nozzles is to be a component of a sampler calibration strategy.

3.4 Summary of WSC Method

The WSC method is basically sound and is operationally attractive and should form the basis for a new calibration strategy. Some additional research is required to establish the accuracy attainable before a calibration strategy can be formulated. Particular emphasis must be placed on the fact that existing calibrations were obtained for samplers with brass nozzles, whereas the present practice is to use plastic nozzles.

4.0 RESEARCH REQUIREMENTS

It is hoped that the accuracy of determining the calibration coefficients K and C_N can be increased from the 10% obtained by WSC prior to 1972, to a value of 5% at the 95% confidence level. The information required to obtain a complete understanding of the performance characteristics of each type of sampler to establish a complete calibration should be considered in two parts: 1) short term research; and 2) long term research. In the first case, the results will be used to establish the calibration methodology in the towing tank and the calibration of the nozzles. In the second case, the research will provide answers on the effect of turbulence, sediment concentration, particle size, particle size distribution and temperature.

If the effect of any of these properties on the performance of a given sampler is significant, then appropriate modifications to the short term procedure can be made. In the meantime, the calibration method based on the short term research can be used for an interim data gathering program. If significant adjustments are indicated then the data can be corrected accordingly.

The primary objective at this time should be to refine the WSC method and therefore, efforts should be concentrated on the short term research component. Short term research is equivalent to a determination of the uncertainty in the value of K in equation (5) and the nozzle coefficient C_N in equation (10) during the calibration process.

The quality of a calibration of a sampler with a specific nozzle at a given velocity, can be measured by the repeatability of the values of K and C_N at that velocity. The repeatability is then determined by taking the average of a large enough number of samples, say 20, together with the confidence limits at the 95% confidence level. If the 95% confidence limits provide sufficient accuracy, then any subsequent measurement that falls inside these limits will be satisfactory. The tests on the nozzles should include establishing the variability of C_N obtained with different nozzles of the same type and size. Considerations should also be given to determining if values of the coefficients C_N for the plastic nozzle remain stable with time for normal operating conditions.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Using dimensional analysis and a review of the WSC method of suspended-sediment sampler calibration, a research program has been developed as a first step toward a new more comprehensive calibration strategy as outlined in Figure 9. It was established that the WSC method used up to 1972 should be used as the basis for this new strategy. It is recommended that the research program consist of a short term component and a long term component. The short term component will provide the necessary information for the determination of the sampler and nozzle calibration coefficients respectively. The long term component will provide the information regarding the effects of turbulence and sediment properties. The result of this research will provide the required input for a comprehensive calibration strategy.

ACKNOWLEDGEMENTS

The writer wishes to thank C. DeZeeuw for his description of the WSC calibration method which was primarily developed by him while he was employed by WSC at the towing tank facility in Calgary, Alberta.

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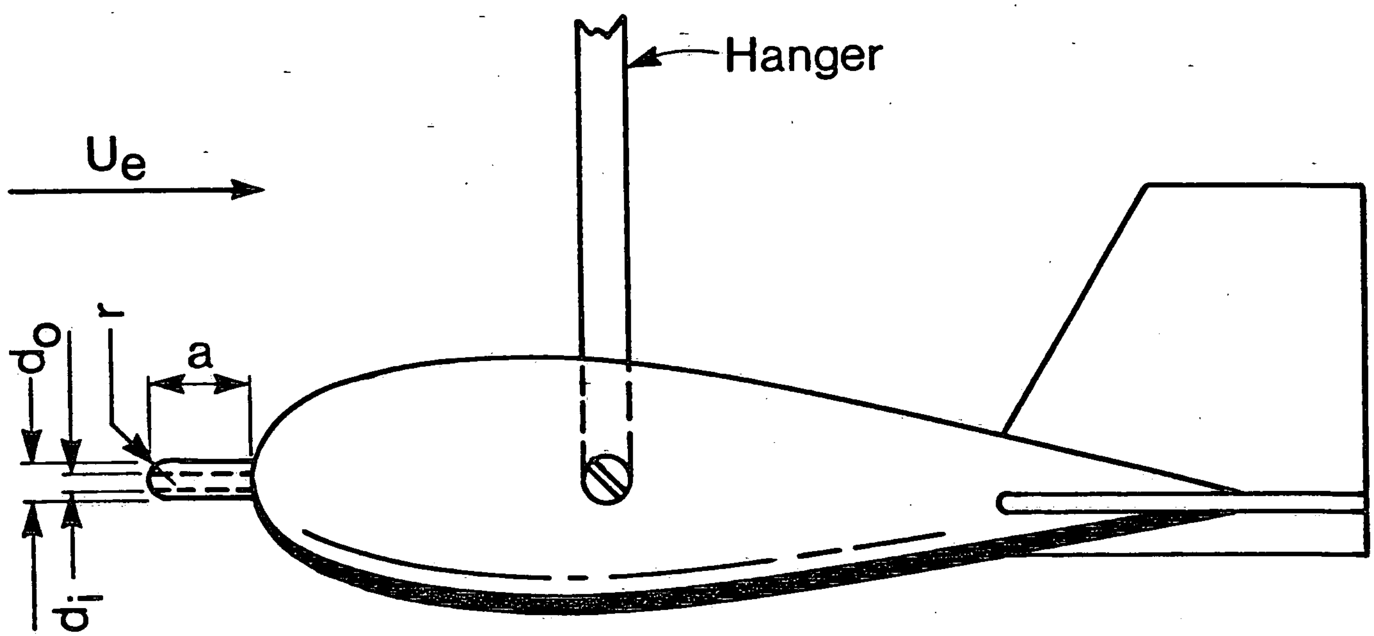

Figure 1 Schematic of Sampler and Nozzle

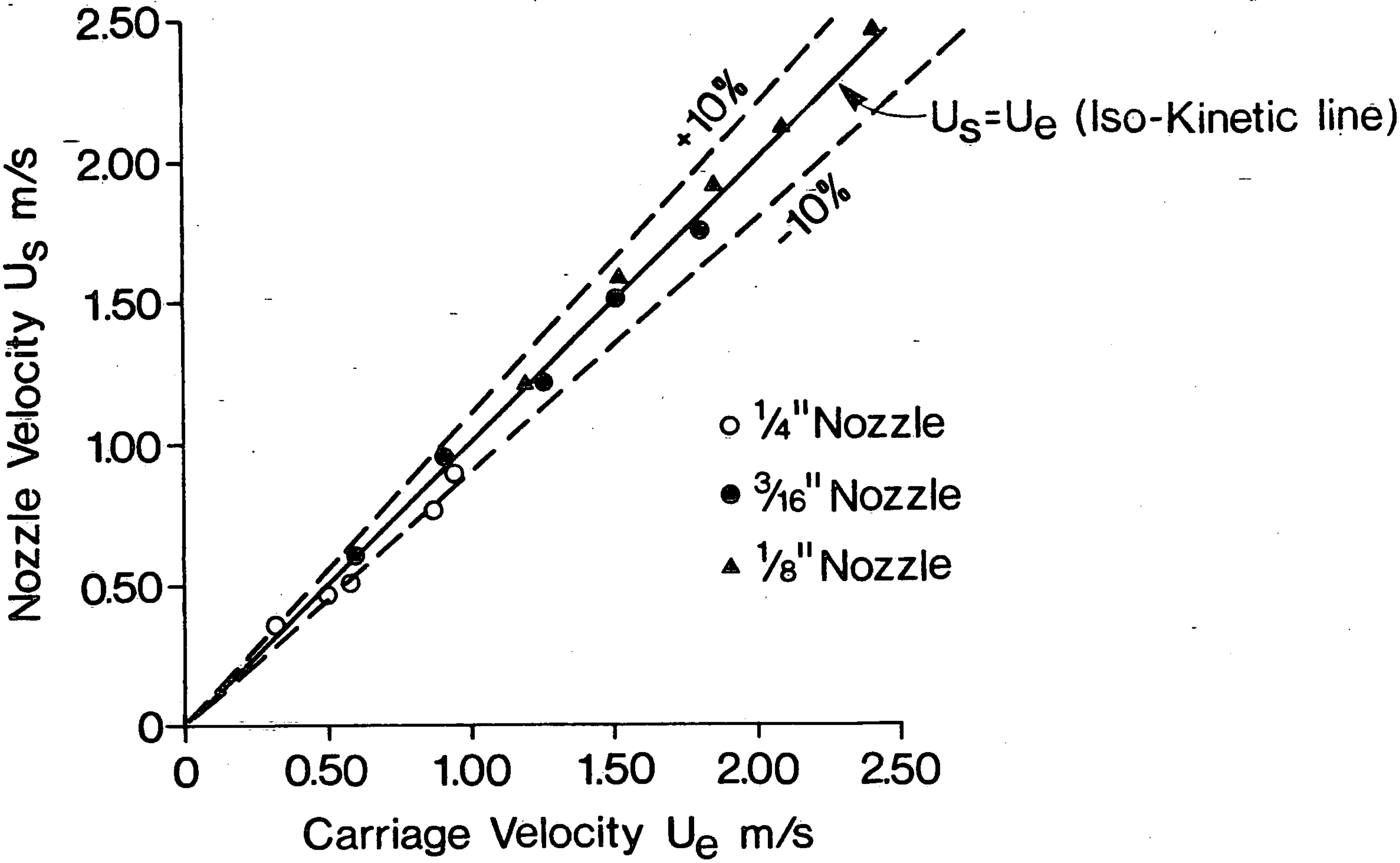

Figure 2 WSC Calibration for DH48 Sampler with three standard nozzles.

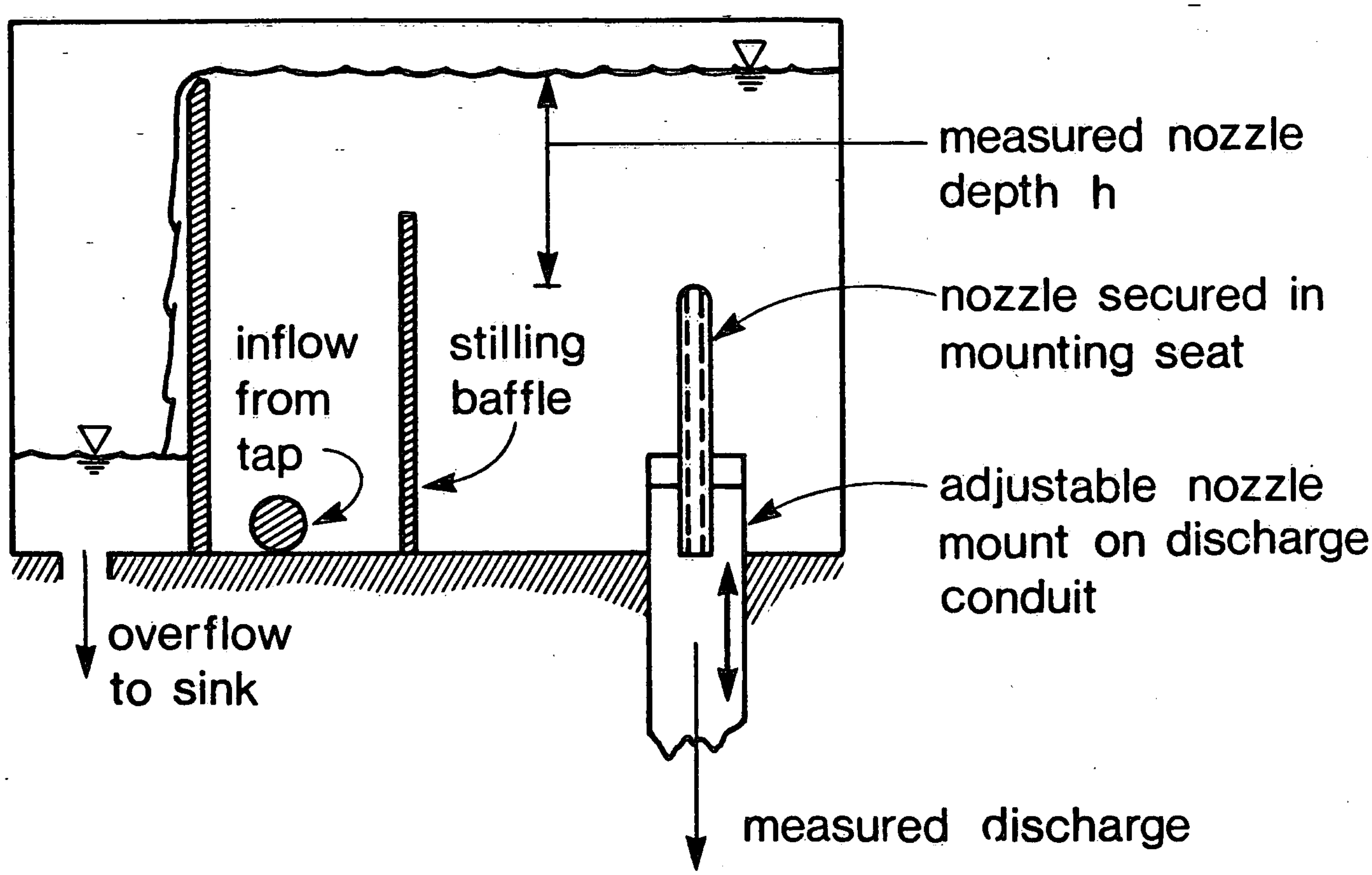

Figure 3 Schematic of WSC Constant Head Tank

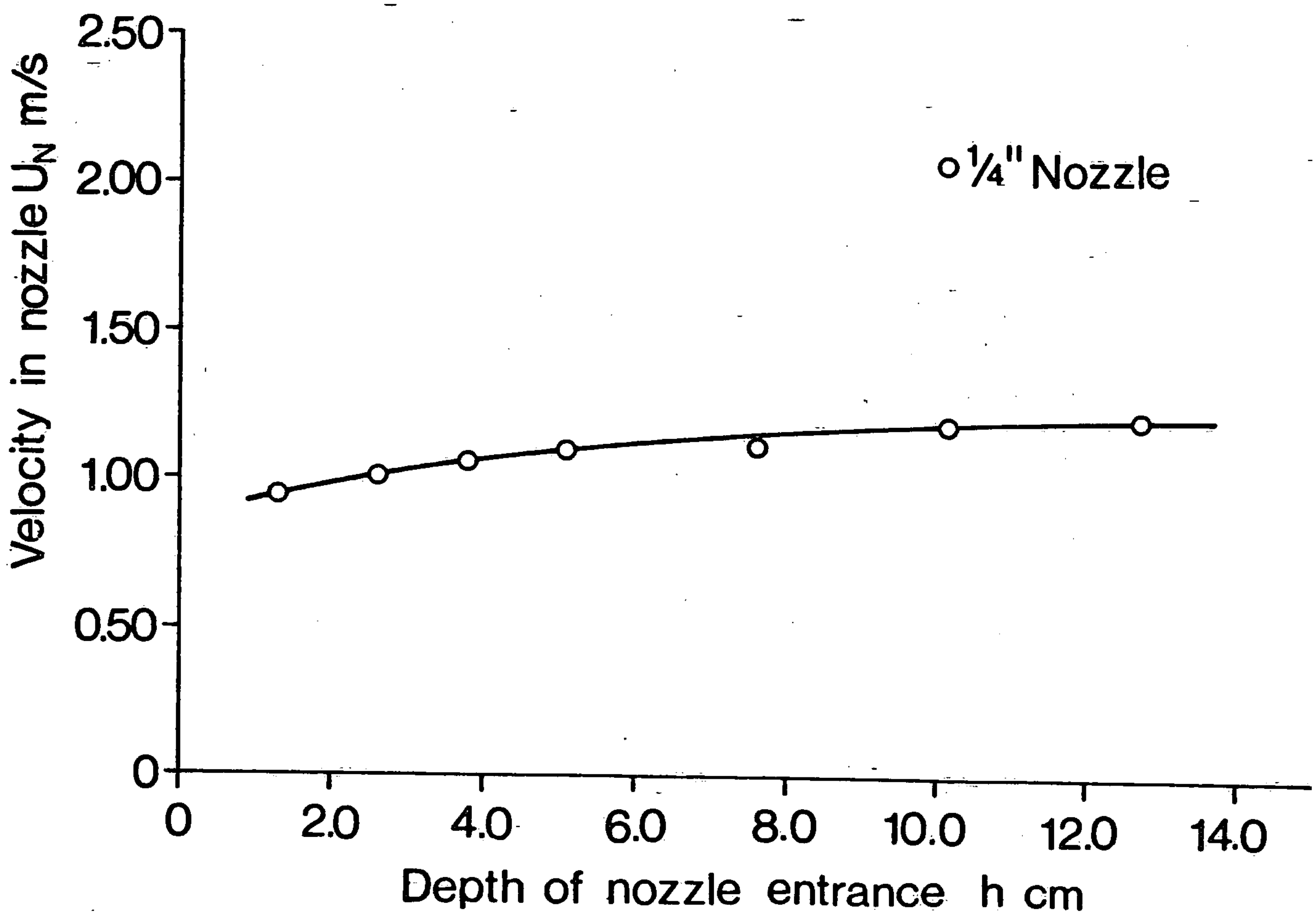

Figure 4 Calibration Curve for ¼" Nozzle obtained in WSC Constant Head Tank

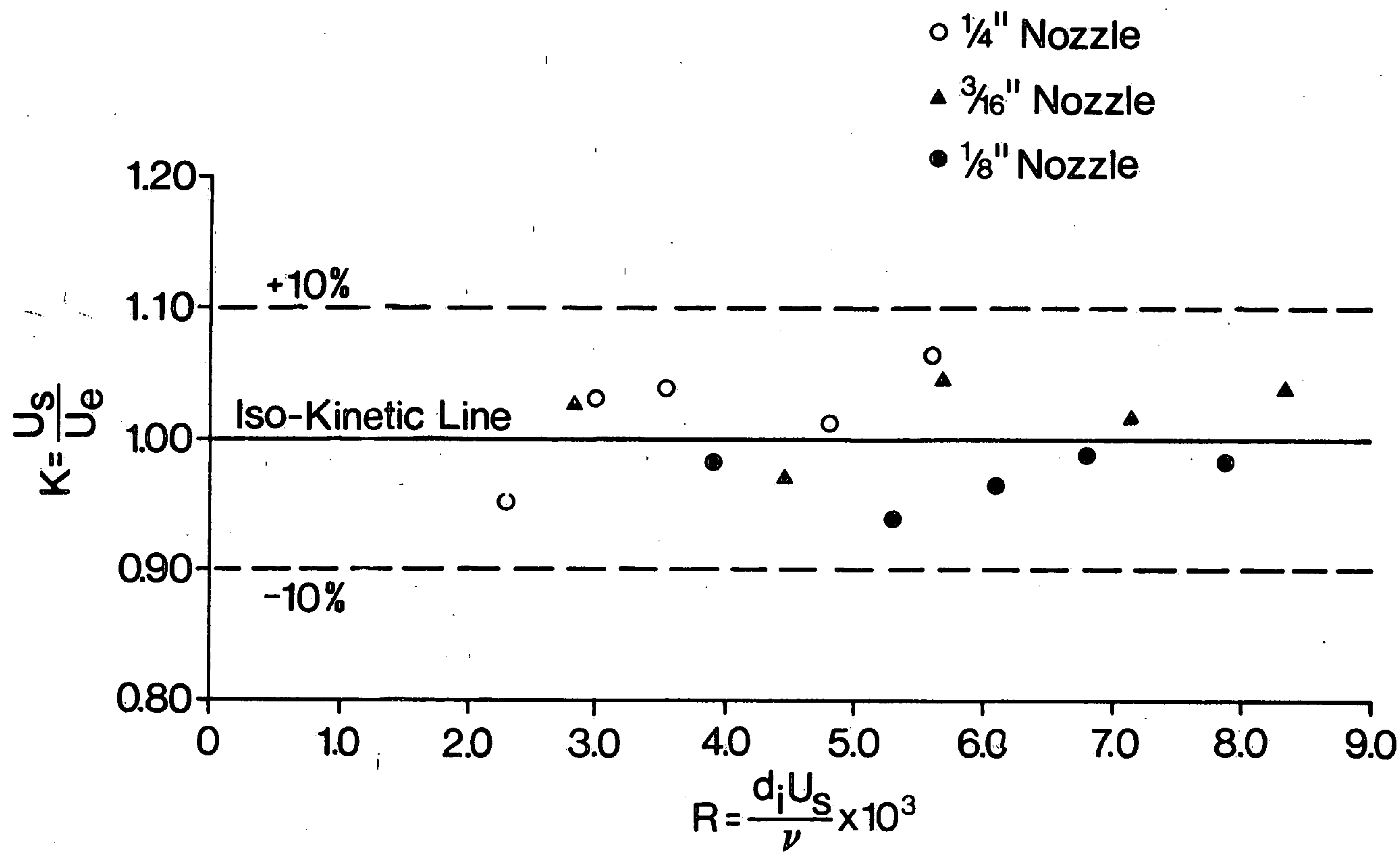

Figure 5 Variation of Calibration Coefficient K

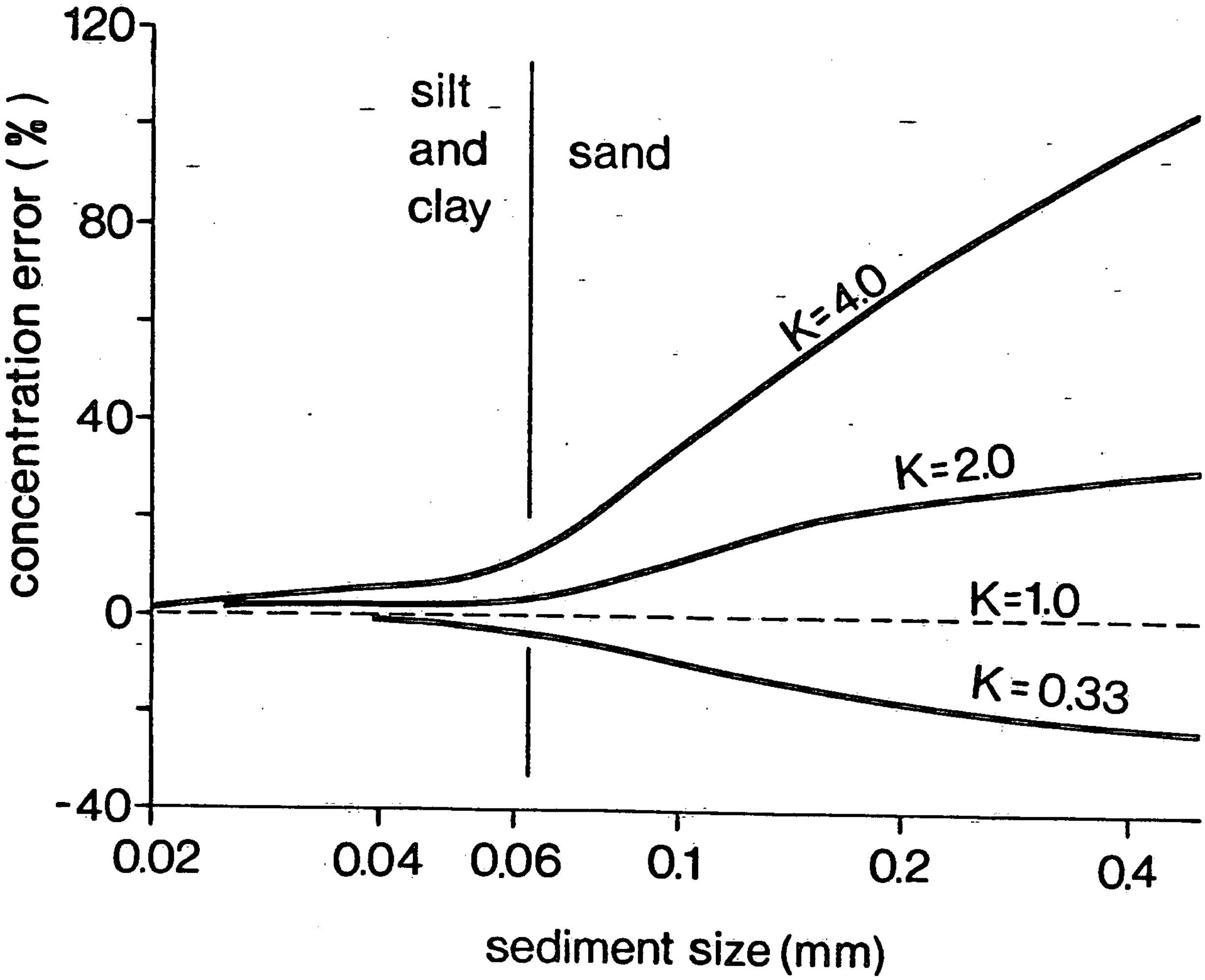

Figure 6 Errors due to over and under sampling (from Guy and Norman, 1970)

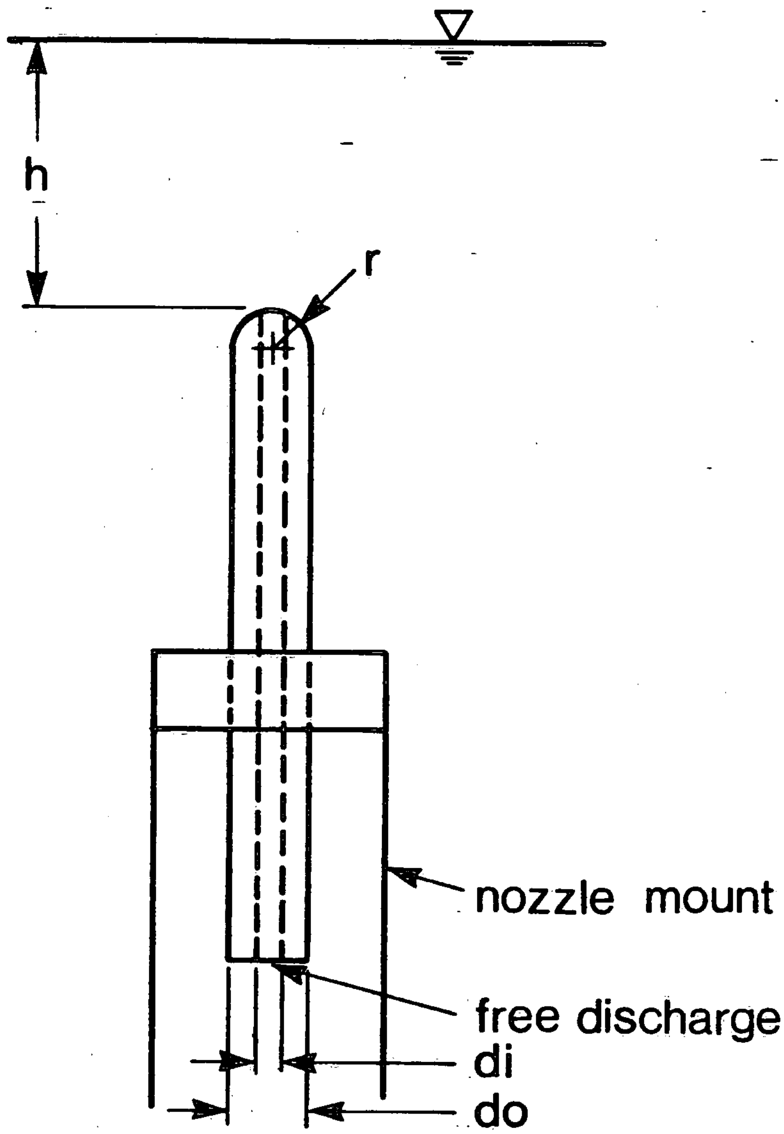

Figure 7 Schematic of Geometric Variables for Calibration of nozzle in WSC Constant Head Tank.

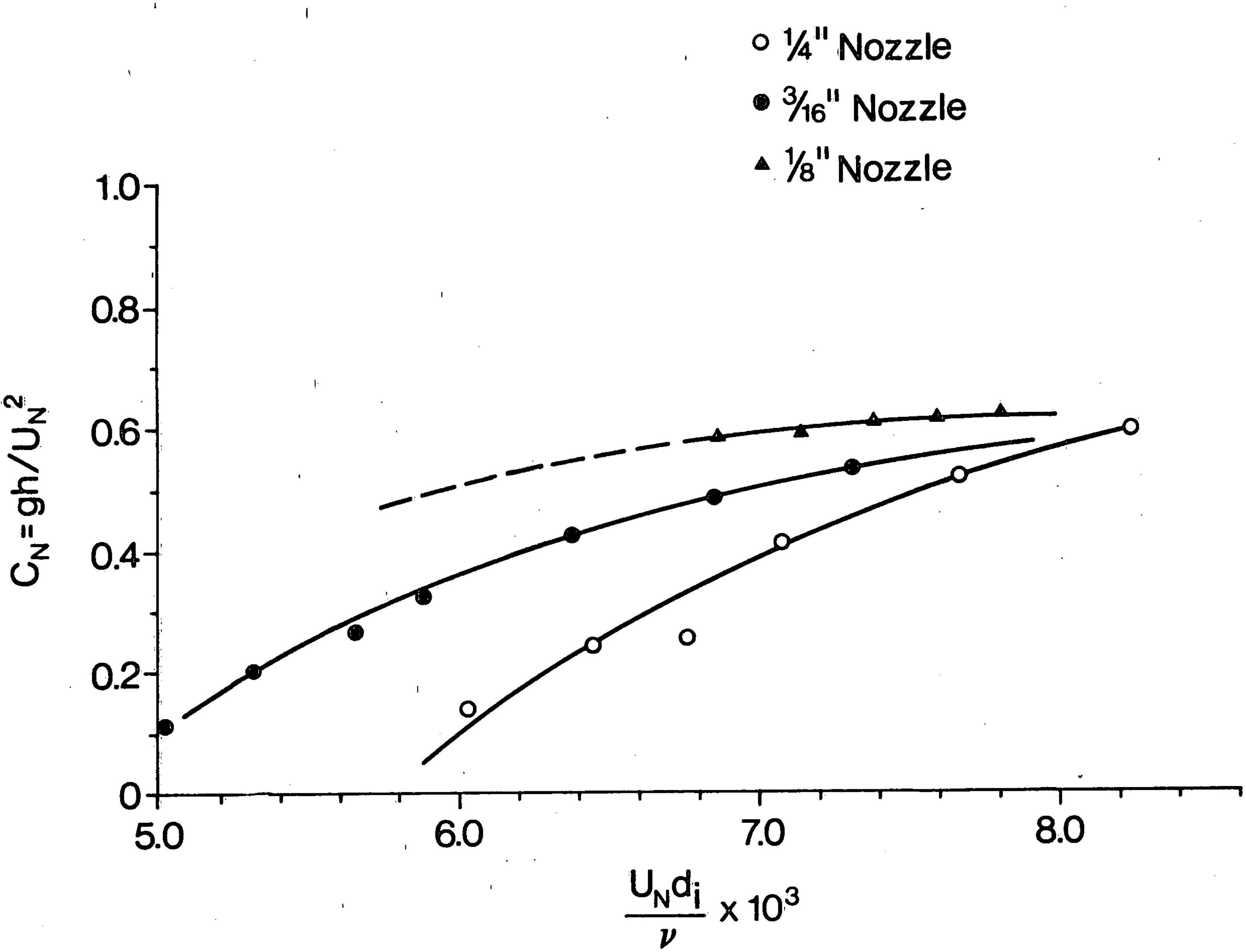

Figure 8 Variation of Nozzle Coefficient

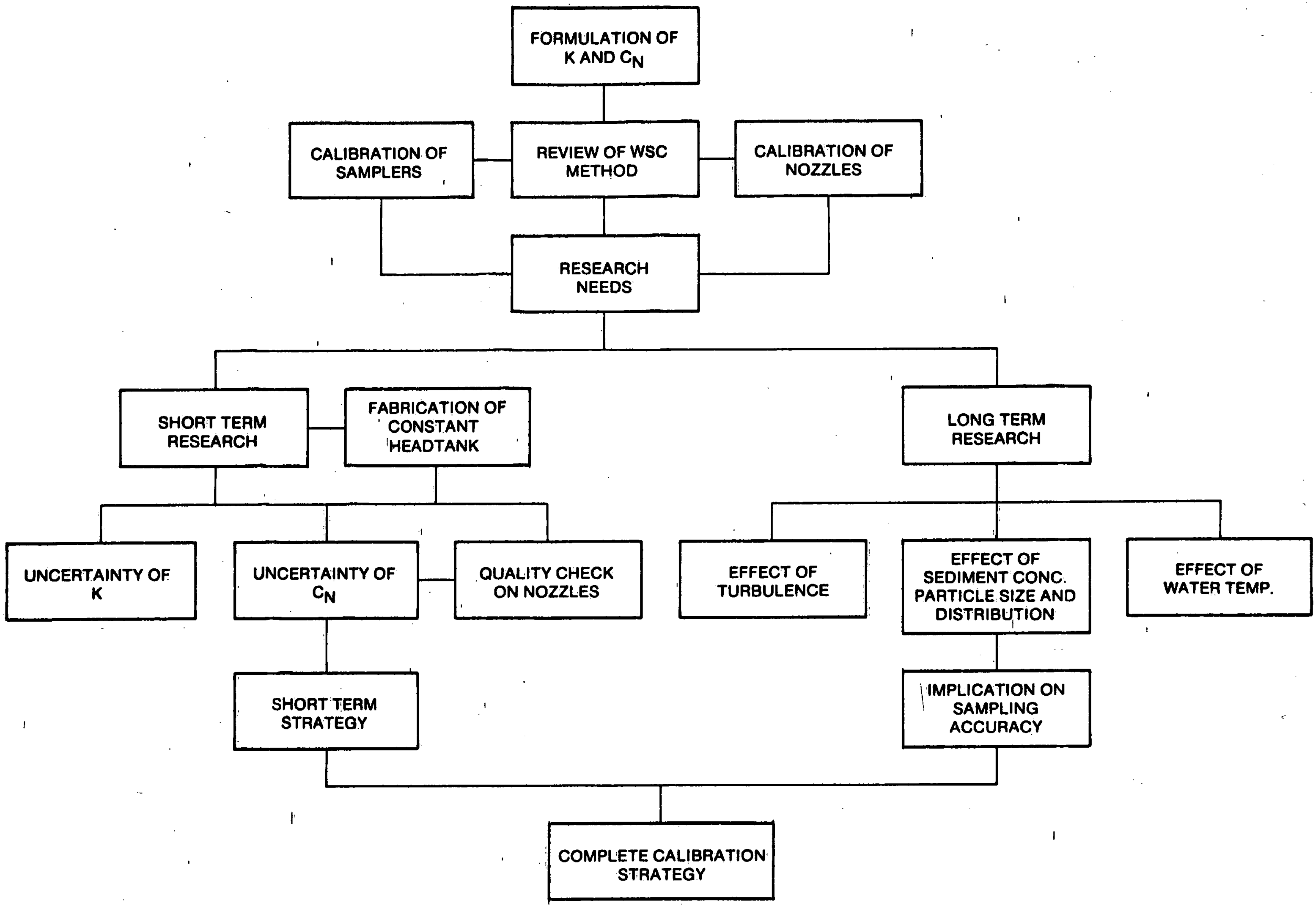

Figure 9 Development of Calibration Strategy - Phase I