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Experimental Errors in Measurement of Alluvial Channels

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1.0 INTRODUCTION

In order to study the behaviour of rivers and other large alluvial channels, it is necessary to measure hydraulic, sediment and morphologic quantities. Measures of physical quantities are never free from uncertainties. To meaningfully apply the information obtained from these measurements, either directly or through derived predictive equations, it is necessary to know the degree of uncertainty involved. The estimation of error in measured physical quantities is therefore an integral part of research involving measurements of alluvial channel phenomena.

1.2 The errors in measurement of physical quantities are classified as random and systematic errors. The random errors are the deviations from true quantities caused by a lack of sensitivity of the measuring equipment and chance fluctuations. The systematic errors are caused by the characteristics of particular measuring instruments used. In addition to systematic and random errors, another source of error is the sensitivity of derived quantities to discretization and computational procedures. These errors are herein called the procedural errors.

1.3 Procedural errors are primarily caused, when a continuous variable is estimated using a number of discrete measurements. Examples of such estimate in alluvial channel measurements are: the estimation of area of cross section, water discharge, and sediment load. In each case, the physical quantity in question is measured at discrete points in the channel and the desired value is estimated by a numerical procedure based on a phenomenological structure of the quantity being measured.

1.4 In this paper prominent systematic, random, and procedural errors in the measurement of basic and derived quantities, such as measurement of width, depth, area of alluvvial channel cross section, average velocity of flow in a vertical, energy gradients, discharge of water flowing through a section and bed material load have been elaborated.

For the estimation of above narrated errors research is underway in Alluvial Channels Observation Project (ACOP), WAPDA.

.0 EXPERIMENTAL ERRORS

.1 Nature of Experimental Error

According to International Standards Organization (ISO) (10):

"No measurement of a physical quantity can be free from uncertainties which may be

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associated with either systematic bias caused by errors in the standardizing equipment or a random scatter caused by a lack of sensitivity of the measuring equipment. The former is unaffected by repeated measurement and can only be reduced if more accurate equipment is used for the measurement. Repetition does, however, reduce the error caused by random scatter."

Mandel (11) has described the nature of experimental error in a more general way. According to him, it is useful to look upon a method of measurement as a process involving three basic elements. The first element is the unknown quantity, Q, which is the object of the measurement. Generally Q enters the measuring process in the form of a sample or specimen, or of a physical system. The second element is the numerical value, M, obtained by applying the measuring process, in accordance with a given set of instructions, to the specimen or the system. Of course, M is a function of Q, but even in the most precise methods of measurement there always exist factors other than Q, and related to environmental conditions, that have an effect on the measurement M. Let the totality of these environmental factors be denoted by the letter C keeping in mind that C represents not a single variable, but rather a vector in a space with a large number of dimensions. The vector C is the third element involved in the measuring process. For any given value of the vector C, say C_0, the measurement M can be considered to be a mathematical function of Q, $M=f(Q/C_0)$. it is assumed herein that this function is monotonic in Q over the entire range of validity of the method of measurement, since a nonmonotonic function would be of little practical value. As C varies there corresponds to each value of C a curve representing the relation between M and Q. The totality of these curves, for the entire range of C-vectors, constitutes the measuring process.

For a well defined method, the factors constituting C vary over a relatively small range. The value taken by each of these environmental factors during a given measurement is to a certain extent governed by chance. Nevertheless, some of these factors are systematic in that they depend on identifiable entities, such as a given laboratory or instrument, a given day, a given operator, etc.

Measurements corresponding to the same value of Q will not necessarily agree with each other, as they may lie on different M, Q curves. The variability thus produced is known as "experimental error." It is seen that, depending on the extent to which the environmental conditions are controlled, experimental error may be large or small, and is partly systematic and partly random.

When all identifiable components of C are "controlled," i.e., when they are given fixed values to the maximum feasible extent, the remaining components of C may be considered as random variables. Their variability generates a set of curves, which we may call a "bundle," such that it is a matter of chance, which curve of the bundle prevails for any given measurement. In this manner there corresponds to each value of Q, a statistical population of M values, with a particular standard deviation, related to the "width" of the bundle for this Q-value.

The quantities involved in process of measurement are continuous variables in space and time, therefore in addition to systematic and random errors, another source of error is the sensitivity of derived quantities to discretization and computational procedures. These errors are herein called the procedural errors.

Procedural errors are primarily caused, when a continuous variable is discretized and an integral is replaced by summation or a function other than the true function is used. Example of such estimates in alluvial channel measurements are the estimation of, area of cross section, average velocity in a vertical, water discharge, and bed material load.

2.2 Classification of Errors

The prominent errors causing deviations from the true quantity according to discussion in Section 2.1 have been classified into three groups as follows:

1. Random errors of measurement
2. Systematic errors of measurements
3. Procedural errors in deriving the quantities

2.3 Discharge Measurements – Errors in Basic Quantities

Measurement of Depth

Measurements of flow depth are made by mechanical sounding across the stream gauging section in order to define the cross-sectional area through which flow is passing. The depth observation is subject to systematic and random error.

Systematic errors – in alluvival channels a boat measurement is normally carried out to measure discharge. The first source of error is the sounding line which measures the depth. If a light sounding weight is used the velocity will drag the weight and the line will not be truly vertical. This source of error can be reduced by using heavy weight or by using tags as explained by Corbett (4).

The second source of systematic error is the accuracy of the counter used to indicate depth. This can be reduced by calibration. The third source of systematic error is the sinking of weight in soft beds rather than resting on the bottom. This error can be reduced by using flat bottom weights.

Random errors – There are four major sources of random error in measuring depth. The first source is due to the movement of bed configurations i.e., ripples and dunes, during the time taken to complete the measurement from one bank to the other. The second source is due to fluctuation of bat due to disturbances in the water surface. The two causes can be reduced by replication. The third source of this type of error is the feel of a person when sounding weight touches the bottom. The reading of the depth is taken on sounding reel counter, the moment sounding weight touches the bottom. The feel of touch can vary from person to person. This can cause error in depth observation. The fourth source of random error is due to least count of counter. The counter of sounding reel used on alluvial channels can read up to 0.1 ft of depth. Sometimes the depth does not match with tenth of foot and is extrapolated. This causes error in measurement of depth. This source of error can be reduced by using a counter with a smaller least count.

Measurement of distance from initial point

Measurements of distance from initial point are made across a stream gauging station in order to find width and define cross-sectional area through which flow is passing.

Systematic erros – To carry out boat measurement in alluvial channels a tagline is stretched across the canal. The location of boat from an initial point on the tagline across the channel cross section defines the width covered. The tagline stretched across the channel is neither in the horizontal nor in the vertical plane. It sags due to its own weight and is stretched by the drag acting on the boat. Therefore, the location of boat on tagline does not define a point in the vertical plane passing through the defined section.

Random error – The source of random error in this observation is the marking on the tagline. The marking is done by beads at a distance of 5 ft. The location of boat cannot match with 5 ft mark all the time and the distance is extrapolated. This causes error in measurement of distance from initial point. This error can be reduced by marking the tagline at shorter intervals. The estimation for location of boat on the tagline usually gives an error of ±0.5 ft depending on the observer.

Observation of number of current meter revolutions

The number of current meter revolutions are observed in a given time to define velocity of flow. Generally the current meters are of two types, namely: vertical axis current meters (cup type) and horizontal axis current meters (propellor type). The meter may be suspended in the flow in two ways – on a rod or on a weight loaded cable.

The rod mounting is practicable on shallow stream (under 8 ft deep) only. In this case the current meter can be aligned normal to the cross section of measurement. However, if the total velocity vector is oblique to the cross section, the cup type meters do not yield the normal components of velocity. Within small angle of obliquity ($\pm 15^{o}$ depending on the design of meter), the propellor meters record the normal component of velocity. On a cable suspension, the fish weight aligns the meter along the total velocity vector. Both the cup type and propellor meters then record the velocity vector and not the component normal to the cross section.

Systematic errors – Major sources of such errors are changes in the physical characteristics of a current meter, variation in the operation and calibration conditions, existence of oblique currents and the nonverticality of the sounding line.

The current meter response depends unpon physical characteristics, such as the hydrodynamic behaviour of the meter assembly, lubrication and the resistane at the bearings. Systematic errors may be introduced in the velocity measurement by continuous use which tends to alter these characteristics. These deviations can be reduced by recalibration of the meter at frequent intervals. The cable mounted current meters also introduce a systematic error in the measurement of normal velocity, when the velocity vector is oblique to the cross section.

The meters are calibrated by towing in a still water tank, whereas in the field they are held stationary in a flowing stream. Also the placement of the current meter with respect to the geometric boundaries of the streamflow will cause a current meter to respond differently.

Dickinson (6) concluded from a literature survey that the effect of the water surface on current meter appears to be a function of the type of meter, the distance from the measuring point to the surface and the velocity. Different meters under-registered or over-registered but no quantitative figures are reported. Similarly he concluded that the effect of the channel sides and bottim is a function of the above metnioned parameters and of the roughness. Pierce (12) noted deviations in the rating curves of cup-type current meters due to shallow depths and prepared tables of shallow depth coefficients to adjust measurements.

The component of velocity in the direction of channel axis is of main interest in calculation of discharge. Dickinson had indicated that with use of cup-type current meters number of revolutions are overestimated and the use of propellor type current meters leads to underestimation of number of revolutions. Finally the use of lighter sounding weight is another source of systematic error. The methods of reducing air line distance and correction tables are given by Corbett (4).

Random errors – Stream flows are generally turbulent such that the velocity at a point continuously fluctuates. The fluctuations may be of large scale or small scale. Large scale velocity pulsations determined by the dimensions and geometry of the streambed upstream the metering section and small scale velocity pulsations are determined by the viscosity of the fluid. The order of magnitude of the period of large-scale pulsations determines the optimum duration of exposure of current meter for average velocity observation at a point in the vertical.

As the turbulence is more intense near the boundaries, the random error in velocity is expected to be larger at the points in this vicinity. Regarding exposure time Dementev (5) concluded that on mountain rivers an exposure time of 100 to 200 seconds could give 5 to 10 percent error in point velocities and 4 to 6 percent in mean velocity over a vertical.

For the alluvial channels of Pakistan which are constructed in areas with flat topography, the exposure time of 120 seconds is maintained for point velocities in order to minimize such error.

2.4 Discharge Measurement – Errors in Deirved Quantities

As stated earlier the derived quantities are the area of cross section, average velocity and water discharge. The procedural errors in the computation of these quantities are discussed next.

Area of cross section

The cross section of a straight alluvial channel normal to the mean flow direction is schematically shown in Fig. 1. The area of the section is given by

$$A = \int_{o}^{W} d(x)dx \qquad (1)$$

where d(x) is the depth of flow at a distance x from a bank.

In practice the area is observed by a number of discrete measurement of distance from initial point and the depth at that point. For simplicity, it is assumed that the measurement verticals are equally spaced across the water surface width. The area of the cross section, A, is then estimated by a numerical integration scheme as:

$$\hat{A} = [\tfrac{1}{2}(\hat{d}_1 + \hat{d}_N) + \sum_{i=2}^{N-1} d_i]\delta W \qquad (2)$$

where $\hat{A}$ is the estimated value of true area from the measurement process, $\hat{d}_i$ is the depth of flow at the its vertical, i=1,2. .N and δW is the constant spacing between adjacenct verticals. Depending on the shape of the channel at the end verticals, $\hat{d}_1$ and $\hat{d}_N$ may or may not be equal to zero.

The relative procedural error in $\hat{A}$ is defined as

$$\varepsilon_{pA} = \frac{\bar{A} - \hat{A}}{\bar{A}} \qquad (3)$$

The value of ϵ_{pA} is dependent on the shape of the channel cross section and the number of verticals N used in calculating $\hat{A}$. For example, in a rectangular cross section, only one vertical needs to be measured to obtain $\epsilon_{pa} = 0$. In irregular shapes, on the other hand, a large value of N may be needed to yield a reasonable value of ϵ_{pA}.

Average velocity in a vertical

The average velocity in a vertical is generally derived by the two point method. In this method, the velocity is measured at two points located at 0.20 and 0.80 times the local depth, below the water surface level. The history of development of this method and its utility in measuring velocity has been reported by Apmann (2).

The observed velocity is given as :

$$\bar{\hat{V}}_i = [\hat{V}_{i(0.2)} + \hat{V}_{i(0.8)}]/2 \qquad (4)$$

where $\bar{\hat{V}}_i$ is the mean observed velocity,
$\hat{V}_{i(0.2)}$ is the observed velocity at 0.2 of depth below surface, and
$\hat{V}_{i(0.8)}$ is the observed velocity at 0.8 of depth below surface.

Therefore procedural error in velocity E_{pv} can be expressed as

$$E_{pv} = \bar{\hat{V}}_i - \bar{V}_i \qquad (5)$$

where E_{pv} is the procedural error in velocity and $\hat{V}i$ is the true velocity.

Water discharge

The water discharge through a channel section is a continuous function and can be expressed (see Fig. 1) as

$$Q = \int_0^W \int_0^{d(x)} v(x,y)\,dxdy = \int_0^W V(x)\,d(x)\,dx, \qquad (6)$$

where v(x,y) is the velocity normal to the cross section and V(x) is the average velocity in a vertical at a distance x from the bank. In practice, the water discharge in a channel is evaluated by measuring the local depth and the average velocity on a number of verticals in the cross section. Unlike the evaluation of area, two methods of numerical integration are available for the evaluation of water discharge from discrete observations. These methods give

$$\hat{Q}_1 = \delta W[\tfrac{1}{2}(\hat{d}_1\hat{\bar{V}}_1 + \hat{d}_N\hat{\bar{V}}_N) + \sum_{i=2}^{N-1} \hat{d}_i\hat{\bar{V}}_i] \qquad (7)$$

and

$$\hat{Q}_2 = \frac{\delta W}{4} \sum_{i=1}^{N-1} (\hat{\bar{V}}_i + \hat{\bar{V}}_{i+1})(\hat{d}_i + \hat{d}_{i+1}) \ , \qquad (8)$$

where $\hat{Q}_1$ and $\hat{Q}_2$ are the derived values of Q on N verticals and d_i, V_i are the depth and average velocity of flow at the ith vertical, respectively. The relative procedural errors in using Eq. (7) and (8) are ϵ_{Q1} and ϵ_{Q2} defined similar to Eq. (3).

2.5 Energy Gradient – Errors in Basic Quantities

Water surface elevation

The general method used for this measurement is by observing the water surface level at a number of points along a canal bank with reference to a datum and the horizontal distance between these points. Of the two basic quantities, the relative error in the measurement of water surface elevation is always large in the flat slopes of Link Canals and is a major contributor to the relative error in measured energy gradient.

Systematic errors – The water surface elevation is generally established from measurement by a peg forced into channel boundary. However, it is observed that the peg sinks into the alluvium under weight of the staff thereby introducing an error. This error can be reduced by devising a system such as given in ACOP report (1). In this system a perforated pipe is fixed near the bank to serve as a stilling well in which the water surface level is observed by a micrometer. In the measurement of a wavy surface, the general tendency would be to measure the wave troughs too high and thus introduce an observer dependent systematic error. However, with gradient calculation, the difference of water levels between two consecutive points is used and the systematic error is thus largely eliminated.

Random errors – Fluctuations caused by wind, unsteadiness in flow and the change in bed forms create fluctuations in the water surface level. Although the changes in water surface level around the mean are small they can cause a substantial error if water surface level observations at various stations are out of phase. Random error may also be introduced due to nonverticality of the staff held on a peg.

Distance along bank

The distance along the bank is measured by precise chaining and the absolute values of distance measured are large. Therefore, both the relative systematic and random errors are negiligible.

2.6 Energy Gradient – Errors in Derived Quantities

Theoretically the slope or energy gradient is the line joining the points representing instantaneous true energy levels at the two ends of a reach. However, in practive the energy gradient is calculated from water surface levels observed on a number of points and the mean velocity of flow in the reach. Therefore, the relative error ϵ_s in energy gradient is

$$\epsilon_s = \frac{E'G\text{-}EG}{EG}$$

where EG' = energy gradient calculated from water surface levels observed at number of points one after another and

EG = energy graident calculated from instantaneous water surface level observations at two ends of reach.

2.7 Bed Material Load – Errors in Basic Quantities

Concentration and particle size distribution

The sediment concentration and particle size distribution is calculated from the analysis of water sediment samples collected in the field. Field methods of collecting sediment are given in detail by Guy and Norman (9) and the methods of sediment analysis are explained in USGS publication (8).

Systematic errors – The systematic errors are introduced when the weight of sampler is insufficient to keep the verticality of sounding line, the nozzle size selected is not proper and the required laboratory temperature is not maintained for the analysis.

Non verticality of sounding line results in a non-representative sample, selection of improper size nozzle fills in a volume in bottle smaller or bigger than the desired and temperatures maintained for analysis other than recommended give rise to erroneous results. These errors can be controlled by following the prescribed procedures.

Random errors – These errors depend on spatial and temporal distribution of suspended sediment particles, methods of collection of suspended sediment sample and their analysis.

The sediment is kept in suspension by vertical component of the eddies. Therefore the sample collected during one particular interval of time may have a different concentration than the one collected later.

The methods in use for manual collection and analysis of sediment samples involve extensive use of judgement by the operator. For example, maintenance of equal transit rate on all the verticals in ETR method of sampling, keeping unsampled depth as 4 inches from bed, marking of layers of sediment as it settles in visual accumulation (V.A) tube method of particle size analysis and withdrawal of samples from apparatus in bottom withdrawal(B.W) method or Pipet method according to specified time require personal judgement.

Temperature

The kinematic viscosity which is used in the calculation of the sediment load passing through a cross section at a particular instant is temperature dependent. The temperature of water is usually observed with a mercury thermometer placed in water near the bank.

Systematic errors – Such errors are introduced in the use of mercury thermometer because of their inability to provide continuous monitoring of temperature. Thermocouples and thermisters offer much more versatility and help reduce these errors. In a study made on the distribution of temperature in the cross sections of the Pakistan Link Canals by using thermisters, showed that there were no appreciable temperature gradient so that the practice of measuring the water tempratures near the banks does not introduce any significant systematic errors.

Random errors – These errors are introduced if a thermal gradient exists in canal waters.

However, these errors are negligible in alluvial channels.

2.8 Bed Material Load – Errors in Derived Quantities

An accepted method of determining the bed material load in alluvial channels (3,9) is to measure the suspended load up to 4 inches from the local bed with U.S. D-49 sampler. The surface layer of bed material is simultaneously sampled and concurrent measurements of water discharge, slope and temperature are made. The unmeasured load in the unsampled 4 inch depth close to the bed is then estimated from a somewhat changed version of Einstein's bed-load function (7). The sediment load in a channel is a continuous variable same as the cross-sectional area, velocity and water discharge. Two methods of discretization are available in this case. In the Equal Discharge Increment (EDI) method,the cross section is divided into N segments containing equal proportions of water discharge and the depth integration sample is obtained at the vertical representing the centroid of discharge at each segment. In the Equal Transit Rate (ETR) method, the depth integrated samples are obtained at N equispaced verticals, These samples are composited and analyzed on the basis of average sampled depth (9).

The bed material load is a nonlinear function of the hydraulic flow and bed material parameters. The averaging of samples obtained from different verticals by compositing in ETR method introduces a procedural error. Similarly the representation of an irregular segment by a rectangular segment with depth at the centroid of the segmented discharge in the EDI method introduces a procedural error. The magnitude of these errors depends on the degree of non-uniformity of sediment concentration in the cross section, the irregularity of the channel cross section and the number of sampling verticals used. Evaluation of this procedural error can only be made by direct computations in a given case and cannot be generalized. Similarly the random error in bed material load can only be estimated by numerical methods.

3.0 CONCLUSIONS

3.1 The experimental errors in measurement of alluvial channels have been classified as:

1) Systematic Errors
2) Random Errors
3) Procedural Errors

3.2 The systematic errors can be reduced by using more sensitive equipment as used in ACOP.

3.3 The random errors can be reduced by replication/sufficient exposure times as practiced in ACOP.

3.4 The procedural errors can be reduced through numerical procedures such that the continuous function is represented as a discrete function without losing meaningful results.

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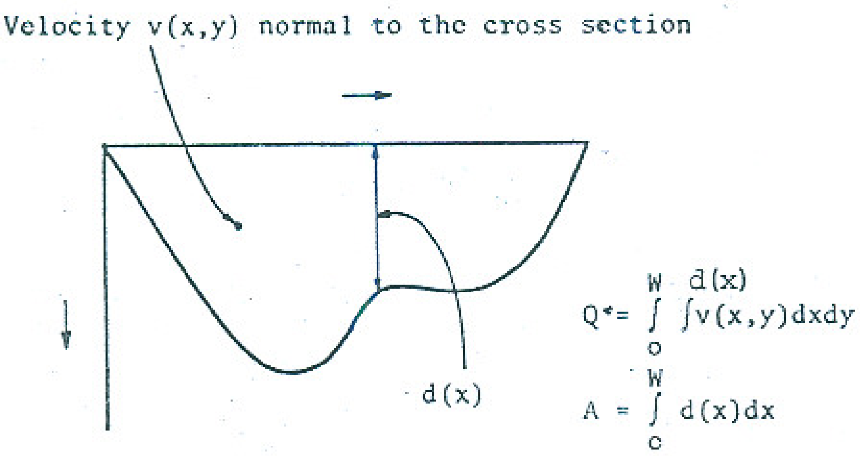
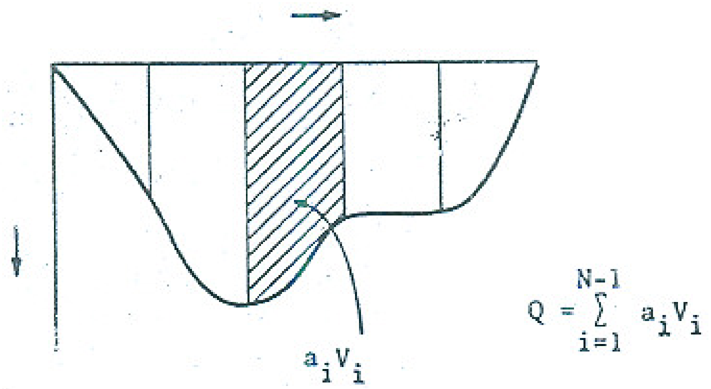


$$Q^* = \int_0^W \int^{d(x)} v(x,y)\,dx\,dy$$

$$A = \int_0^W d(x)\,dx$$

(a) Discharge as an integral of a velocity field over a cross section.



$$Q = \sum_{i=1}^{N-1} a_i V_i$$

(b) Discharge as discretized by number of segments.

Fig. 1. Definition Sketches of Discharge in a Cross Section.