RIVERBANK EROSION: A MODEL FOR THE ZAMBEZI

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INTRODUCTION

With recent increases in the power and availability of computing facilities, computer models which describe and predict the course of earth surface processes are beginning to come of age. For instance, during the past year, long term climatic modelling has become sufficiently accurate to describe and predict the changing global weather patterns consequent upon continental drift. Crowley (1986) has shown that an ice cap can only be maintained over a polar land mass or an enclosed polar sea. Of more direct economic value, the occurance of a disasterous "El Nino" event off the western coast of South America can now be predicted with some certainty from data of winds and surface currents of the Pacific Ocean (MacKenzie, 1986). Modelling of dispersion within the atmosphere can now trace the movement of pollutants and predict the consequences of a nuclear war (Chown, 1985).

Despite these advances in modelling of oceanic and atmospheric systems, models of fluvial processes have generally failed to reliably predict changing stream morphology. This paper examines reasons for the failure of existing fluvial predictive models and describes an alternative approach. With reference to the Zambezi river downstream of Kariba dam, a method is presented to model the process of river bank erosion and predict the probability of future erosion as a function of bank morphology and strength, the river flow regime and other elements of the physical system.

THE RESPONSE OF THE ZAMBEZI TO IMPOUNDMENT AT KARIBA

Kariba dam was closed in December 1958 and water was first spilled on a significant scale in April 1962. Since then, the hydrograph at Kariba reveals a gradual rise in the "base flow" through turbines from some 400 cumec (cubic metres per second) to around 1000 cumec during the 1980's. This increase reflects a rise in electricity generation accompanied by increases in the installed capacity of the dam.

The dam is equipped with six flood gates which are opened at specific lake levels according to a reservoir rule curve and information from the flood warning system within the Zambezi's upper catchment (i.e. upstream of Victoria Falls). Although any of the gates can be partially opened, the Central African Power Corporation

(CAPCO) generally opens a whole number of gates to spill excess water.

The pre-dam hydrograph at Kariba took the form of a gradual rise in water levels as the annual flood from the upper catchment reached Kariba, peaking between March and May. Superimposed on the rising limb of this annual event, a series of flash floods from the tributaries downstream of Victoria Falls created brief but often quite major flood peaks (Nugent, 1986). Limited discharge records are presented in Figure 1 to illustrate the modification of the Zambezi's hydrologic regime by Kariba dam. The opening and closing of flood gates gives the post-dam hydrograph its characteristic stepped form. Fluctuations in electricity generation and hence turbine discharge results in much smaller discharge variation on a weekly cycle.

The sediment discharge of the Zambezi has been reduced by damming at Kariba. The Zambezi river's plateau tract upstream of Victoria Falls carries a very small concentration of sediment estimated at 625 ppm. by volume at high stage and about one tenth this value under low flow conditions (Wellington's report cited by Scudder, 1962). In contrast, the lower catchment tributaries carry large volumes of alluvium and are currently building deltas into Lake Kariba. The impoundment of Lake Kariba created a sediment trap which drastically reduced the volume of sediment available to the Zambezi river downstream of the dam.

The effects of damming on the Zambezi's channel downstream can only be partially assessed. The only data sets which describe the river prior to 1958 are a complete set of aerial photographs taken in 1954 and the river's flow regime at Victoria Falls (since 1925) and Kariba Gorge (since 1948). Analysis of the stage - discharge relationship has revealed that the Zambezi has degraded its bed by some 1.5 to 2 metres since 1958 (Nugent, 1986). The photographic record reveals a widening trend (Guy, 1981; Nugent, 1983). Between Kariba and Mupata gorges, a river distance of a little over 160 kms, the channel has widened by an average of 200 metres, as vegetated land has been eroded from both banks and islands within the channel.

RIVERBANK EROSION AND ECOLOGY

The Zimbabwean bank of the Zambezi downstream of Kariba is maintained as a wilderness area by the Department of National Parks and Wildlife Management (Figure 2). The majority of the land is designated as safari area and is used for sport hunting. Some 219 600 hectares of land, including the most extensive of the alluvial terraces found along the river, is preserved as Mana Pools National Park.

The pools at Mana are former distributary channels, abandoned by the braided Zambezi as it eroded its way laterally into its north bank, probably during the late Pleistocene and Holocene period. Following damming at

FIGURE 1: STREAMFLOW AT KARIBA GORGE FOR SELECTED YEARS BEFORE AND AFTER DAMMING AT KARIBA

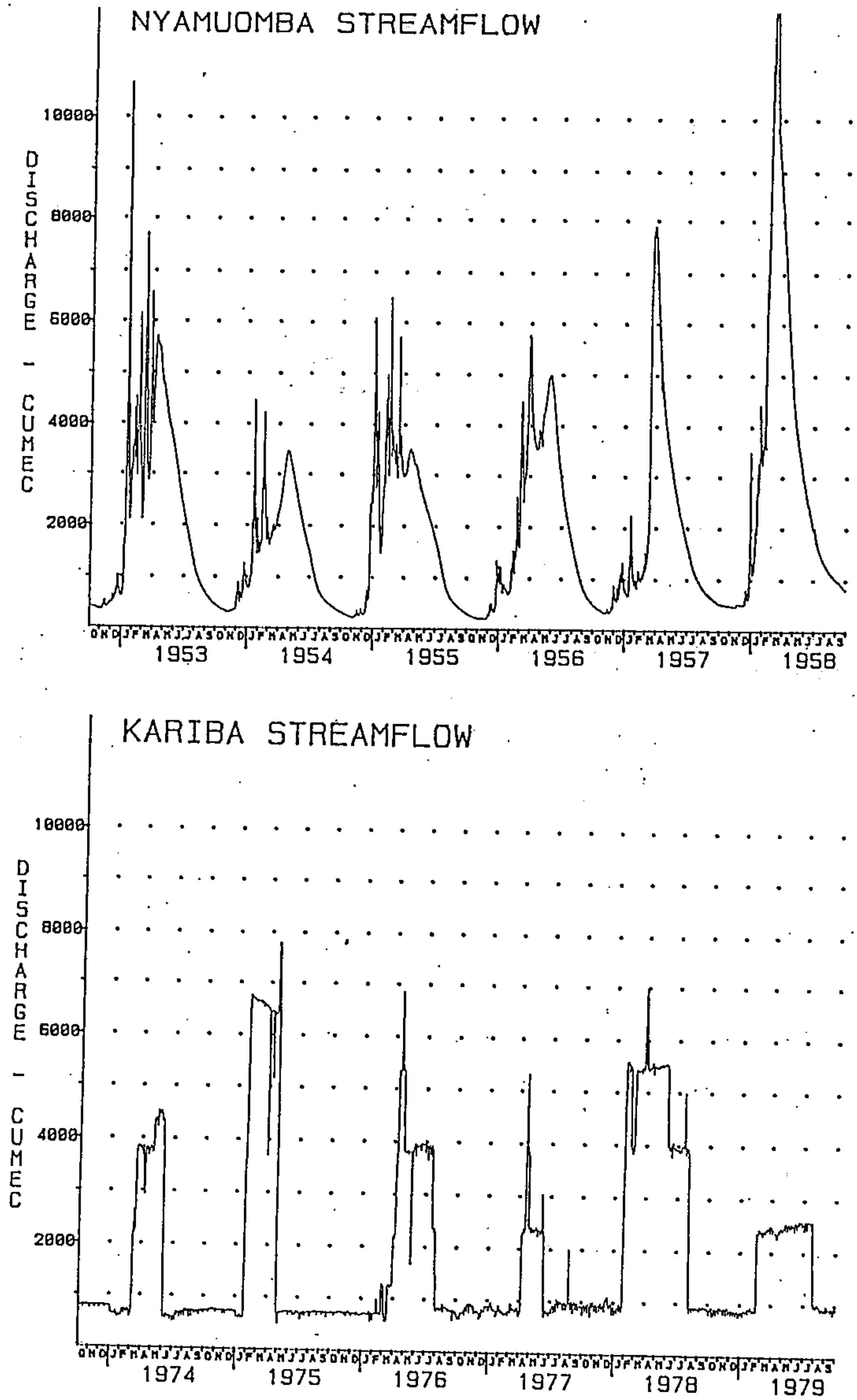
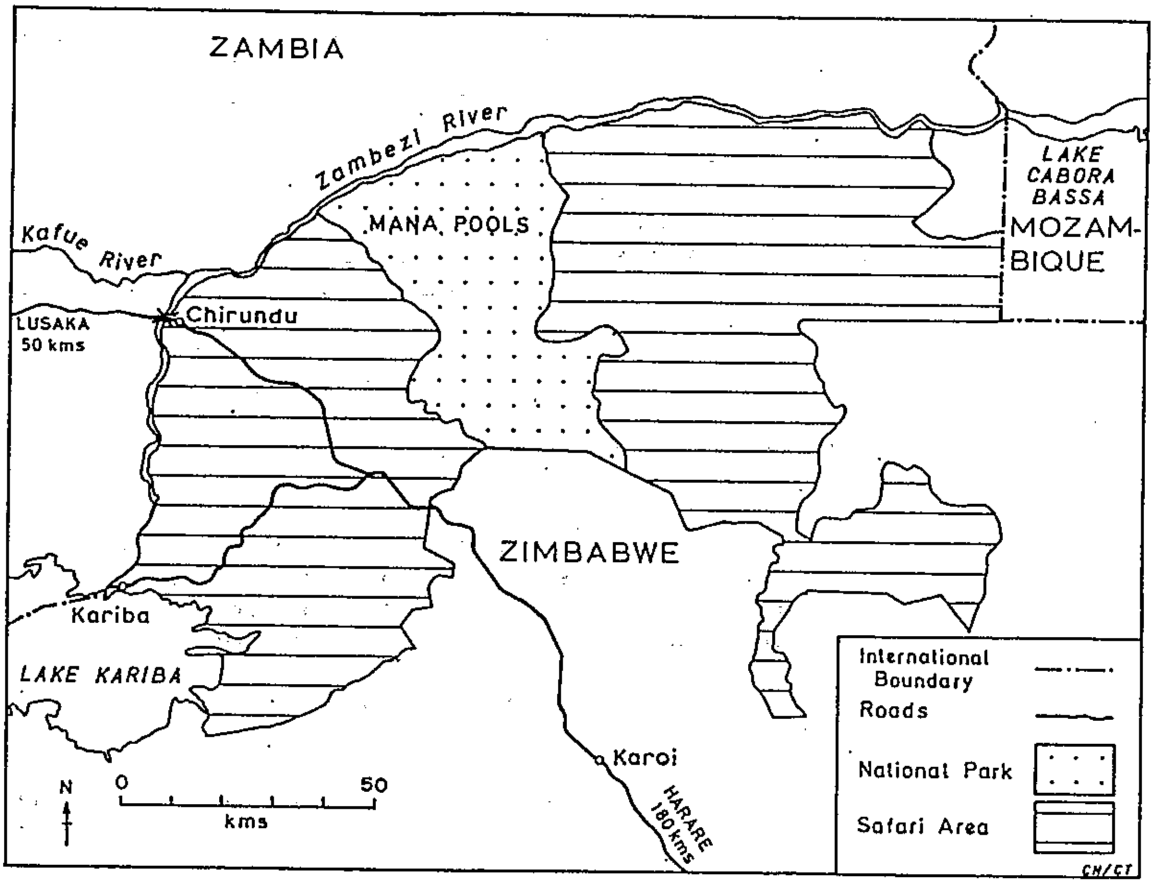


FIGURE 2: NATIONAL PARKS AND WILD LIFE ESTATE ON THE ZIMBABWEAN BANK OF THE ZAMBEZI RIVER BETWEEN LAKES KARIBA AND CABORA BASSA.



Kariba the Zambezi has eroded much of this alluvium as the river has widened by an average of 300 metres along the Mana river front.

The alluvial terraces which underlie the Mana pools support a variety of vegetation types. The oldest terraces, furthest from the river, support a diverse riparian community (Muller and Pope, 1982). Those lying close to the active channel and therefore most liable to be eroded, support only a few pioneer species. Most notable among these is *Acacia albida*.

Acacia albida, also known as *Faedherbia albida* is widespread in Africa from South Africa to the Sudan. This tree, which commonly grows to 30 metres, is generally found in association with water courses (Coates Palgrave, 1977). Unlike other species of *Acacia*, it is deciduous during the wet summer and carries its leaves during the dry season. The seeds ripen towards the end of the dry season.

Animal populations in tropical ecosystems are generally limited by food availability during the dry season. The extensive populations of *A. albida* near the river edge at Mana have resulted in a seasonal migration in which many animal species move onto the Zambezi's terraces during September and October when food and water become scarce in the hinterland. The high protein content of the seeds of the leguminous *A. albida* constitutes the major dry season food source for many of the large herbivores and helps to explain the high ecological carrying capacity of this part of the Zambezi Valley.

If the population of *A. albida* is indeed the major factor limiting animal numbers within the Zambezi valley, it becomes important to the ecological management of the area to be able to answer two related questions:

1. What proportion of the *A. albida* community has already been lost in river bank erosion?

2. How much of the remaining area of *A. albida* woodland is likely to be lost in the future?

The answer to the first of these questions can be deduced by comparing aerial photographs taken in 1954 with the most recent photographic coverage (1982). In order to answer the second question it is necessary to model the process of river bank erosion in such a way as to be able to predict its future course. This will enable the planners to predict the amount of woodland likely to be lost under a range of possible flow regimes through Kariba dam and along the river downstream.

MODELLING RIVER PROCESSES

Two techniques are available for predicting the morphology of a river channel. The first, developed during the last century for predicting the stable form of man-made channels, is the application of the regime equations (summarised by Ackers, 1972). These predict the width, depth and velocity of water in a river as a function of discharge. Recent work on these relationships dates back to the seminal paper of Leopold and Maddock (1953) who summarised the various relationships as :

$$W = aQ^b \qquad D = cQ^f \qquad V = kQ^m$$

Where Q is discharge, W, D and V are the channel width, depth and water velocity and a, b, c, f, k and m are empirically derived constants and exponents.

Much of the subsequent work on these relationships has been devoted to finding the exponents b, f and m which characterise rivers under different physiographic settings. Not surprisingly, these values have been found to vary considerably between and within drainage basins (Park, 1977), as peculiarities such as the nature of the bed and bank sediment, the river flow regime, sediment availability and bedforms present within the channel exert influences which cause aspects of the channel morphology to deviate from "normal" or mean values.

Regime type equations are designed to predict the stable form of a channel at grade, that is, in equilibrium with its surroundings. The dam at Kariba, by modifying the Zambezi's discharge and sediment budget, has disrupted the river's equilibrium and caused the morphological variables to adopt a new relationship with streamflow. Regime type equations cannot be expected to predict the form of a channel under such non-equilibrium conditions.

The second set of techniques, which have been specifically designed to predict change on non-equilibrium channels such as those downstream of dams, can be grouped under the heading of "deterministic models". These are lengthy computer programs which attempt to predict changes in channel morphology by mathematical simulation of channel processes. As much detail as possible is collected to describe the hydrological, sedimentological and topographic variables of the physical system. This then forms the data set of the model and typically includes the form of the channel and flood plain at selected cross-sections and the slope between cross-sections, the granulometric composition of the bed and banks, the channel roughness, the bed load and suspended load carried by the channel at various discharges and the discharges themselves. Deterministic models then use elements of established fluvial theory such as sediment transport equations, flow resistance equations and continuity equations relating velocity to discharge in order to describe channel processes and predict the resultant stable channel form.

The major problem with this method is that channel processes are not sufficiently well understood for deterministic techniques to predict a unique channel response. A river channel may respond to a disruptive influence upstream by altering the value of any of five degrees of freedom; its width, depth, slope, sinuosity and water velocity. Hey (1978) showed that for a unique solution to channel response these five variables should be expanded to nine as the range of depths, bedforms and plan form of the channel are taken into account. In order to predict channel changes, each of these variables must be accurately described by separate equations, which must be solved simultaneously. Hey (1978) rejects deterministic models as predictive tools, as our knowledge of the precise relationships between variables is not sufficiently advanced. He suggests that prediction could be achieved by submitting data to multiple regression analysis.

The problem of predicting channel change would be much reduced if the analysis were limited to variation in a single degree of freedom. The rest of this paper describes a multivariate technique for establishing the relationship between the occurance of riverbank erosion and various measures of the physical system that are believed to influence it. The technique will be extended to predict the most probable effects of future flows and thus map the areas of riverbank most at risk under various possible discharge regimes in the future.

THE STRUCTURE OF THE MODEL

The model takes the form of a multiple regression equation. Graf (1984) gives the structure of an equation, linking the incidence of erosion with elements of the physical system, that avoids the problems of spatial autocorrelation. The dependant variable is the probability of erosion associated with a given area of riverbank. Independant variables must summarise the ability of the water in the channel to instigate erosion and the ability of the bank to resist it. Graf (1984) uses the sum of annual recurrance intervals of the streamflow during the period in question as a measure of the river's hydrology and the distance of each area of land from the riverbank as a measure of bank resistance. Since the technique describes changes in plan form (the removal of riverbank), the amount of erosion that has occured during historic times is taken from old maps or aerial photographs of the area. In the case of the Zambezi river there are at least seven sets of aerial photographs, taken between 1954 and 1982.

Analysis proceeds by dividing the earliest photographic image into squares; any shape would do but squares are easy to use. Each square or picture element (pixel) is characterised by a distance from the channel. Analysis of the second set of photography determines which pixels had been eroded by the time this image was collected. Pixels found each of the various distances from the channel are divided into those eroded and those not eroded to give the frequency with which each of the pixel-distance categories were eroded. These frequencies are associated with the hydrologic regime recorded between the times when the images were collected. The process is repeated as the second image is compared with the third to generate another set of frequencies associated with another flow regime. The process should be repeated as many times as there are images, in order to relate erosion to as great a range of flow conditions as possible. Probability is substituted for frequency and each pixel-distance category is treated as an independant observation in order to determine the constant and exponents of the regression equation, which takes the form:

$$P = a . D^{b1} . H^{b2}$$

Where P is probability of erosion, D is the distance to the channel and H is the hydrological variable. a, b1 and b2 are the constant and exponents of the relationship and are found empirically by standard least squares techniques. Graf (1984) was studying a meandering river and used two distances, one to the nearest channel laterally and one to the nearest channel upstream.

A major advantage of Graf's model is that it seeks to establish a relationship between bank erosion and the causative elements of the physical system on a particular river. A major disadvantage, at least of the form of the model outlined above, is its implicit simplicity. The technique assumes that the probability of erosion of a piece of land can be determined as a function of the river's discharge on a single day of the year (the peak of the flood) and distance from the active channel. This ignores the effects of lesser flows, the fact that bank material varies in its ability to resist erosion and the effects of other elements of the system such as the position of the thalweg within the channel.

The model presented below is an extension of Graf's (1984) technique. The following discussion is an attempt to derive independant variables which characterise the erosion process and also represent the special constraints imposed on the system by impoundment. Since the model is being applied to the Zambezi, it is formulated in terms of the problems associated with large rivers.

HYDROLOGY

Research on the regime equations, which relate elements of channel morphology to discharge, has concentrated on finding a discharge that is representative of channel forming processes. Since high discharges do proportionally more work than low discharges, it would seem to be the peak events which do most to form the channel. Wolman and Miller (1960) have shown that the large amount of work done by infrequent events is compensated for by their rarity and that less severe but more frequent discharges move more sediment over a given period of time and should be taken as channel forming. This has led to the concept of an effective or dominant discharge, established as a compromise between magnitude and frequency.

Riverbank erosion on the Zambezi has been observed to occur at low stage, while no flood gates are open at Kariba, although the probability of erosion is undoubtedly greater at high discharge. Pickup and Reiger (1979) show that it is an oversimplification to link channel characteristics to a single discharge, as the work done by a river is the product of a whole range of flows. Thus the effect of each flow on bank erosion should be considered and the hydrological variable should take the form:

$$\Sigma(Q^{x})$$

Where x is an empirically derived exponent and Q is the daily discharge in cumec. Values of Q at Mana are approximated by the sums of daily streamflow records taken from Kariba and Kafue dams, pre-dam data is taken from the gauging stations at Nyamuomba and Kafue Kasaka. The time period between successive images varies. By summing daily values of discharge, the length of time in which erosion may occur is represented within the independant variables.

Daily streamflow on a large river represents a range of channel conditions, some of which promote bank erosion. It is important to realise however that there is a discharge below which bank erosion will not occur. At this stage the water line probably lies below the base of much of the river cliff. Water velocities along most of the channel are not competant to erode the bed or bank alluvium. The shear stress exerted by the tractive force of moving water on the bed and banks is less than the critical shear stress or shear strength of the alluvium. It is possible that even the lowest discharges experienced on the regulated river lie above this threshold but since this lower limit exists, it should be represented as a constant (C) and subtracted from discharge. Thus the hydrological variable should be represented by :

$$\Sigma((Q-C)^{x})$$

Discharges below this threshold value (ie. when $Q < C$) should not erode the bank at all. The above summation should therefore be made for all days when $Q > C$.

By considering all values of Q experienced during the period under consideration, the problems of magnitude and frequency are no longer relevant. The problem becomes that of finding representative values of C and x. This can be achieved by stepwise techniques. The hydrological variable is calculated for several differant values of C and x and the probability of erosion is regressed against each of these in turn, keeping all other terms constant. The values of C and x which explain the greatest variability in P (i.e. yield the largest values of the multiple regression coefficient) are those that should be accepted and used throughout the analysis.

BANK RESISTANCE

The resistance of the bank alluvium to the flow of water in the channel will affect the probability of that bank being eroded. Resistant banks may be composed of very coarse material, whose mass resists entrainment by the current or very fine material that is cohesive. Intermediate grain sizes are those most liable to be eroded. Grain size is therefore not a good measure of bank resistance.

Yalin (1977) shows that the rate of sediment transport is governed by the shear stress imposed by the water on the bed. A good measure of riverbank resistance to erosion is therefore the bank's ability to resist shear stress, the shear strength of the alluvium.

Thorne and Tovey (1981) have shown how, once undercut, the upper part of the riverbank falls and slides onto the stream margin to present a further obstacle to erosion. The height of the bank is important, as it determines the amount of material that will collapse in this way.

It is apparent from the above discussion that the distance of an area of land from the active channel is not an adequate representation of its ability to resist (or rather avoid) being eroded. Bank resistance should be represented by the product of the volume of material in the bank and its shear strength. A convenient representation is: Distance from the channel (D) x Height of the bank (H) x Shear strength of the alluvium within the bank (SS), DHSS.

In order to illustrate the way this variable should be used, an area of riverbank has been isolated from an aerial photograph taken in 1954. The area consists of five differant terraces, whose mean height and shear strength have been measured in the field and are given in Table 1. The aerial extent of the terraces is shown in Figure 3, in which nominal values have been used to represent each terrace.

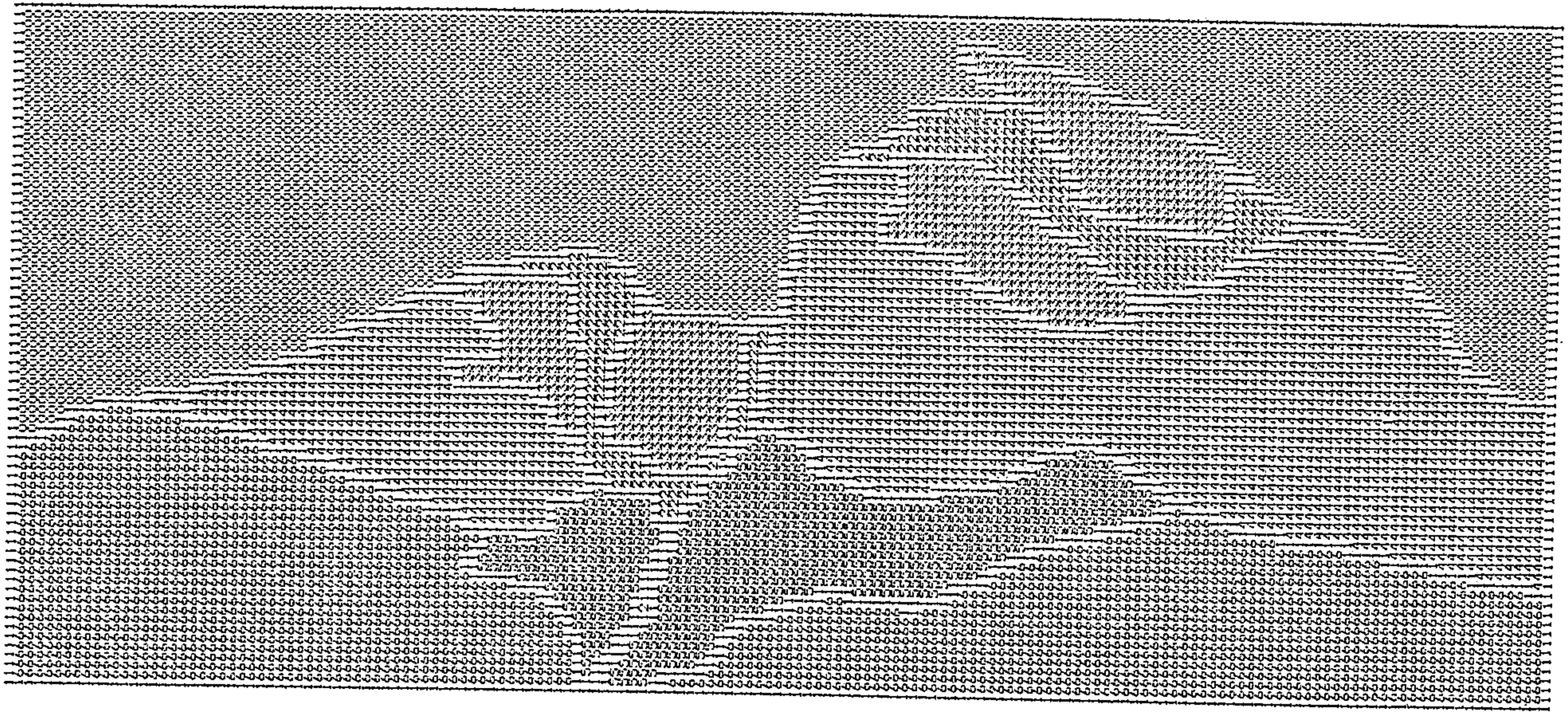


FIGURE 3: MAP OF THE TERRACES FOUND ON AN AREA OF RIVERBANK IN 1954

SCALE: Pixels = 50 m square.

KEY:
0 = Water (Zambezi River)
1 = Boundary Pixels
2 = Unvegetated
3 = Grassland
4 = *Acacia albida* woodland
5 = Riverine woodland
6 = Mopane woodland

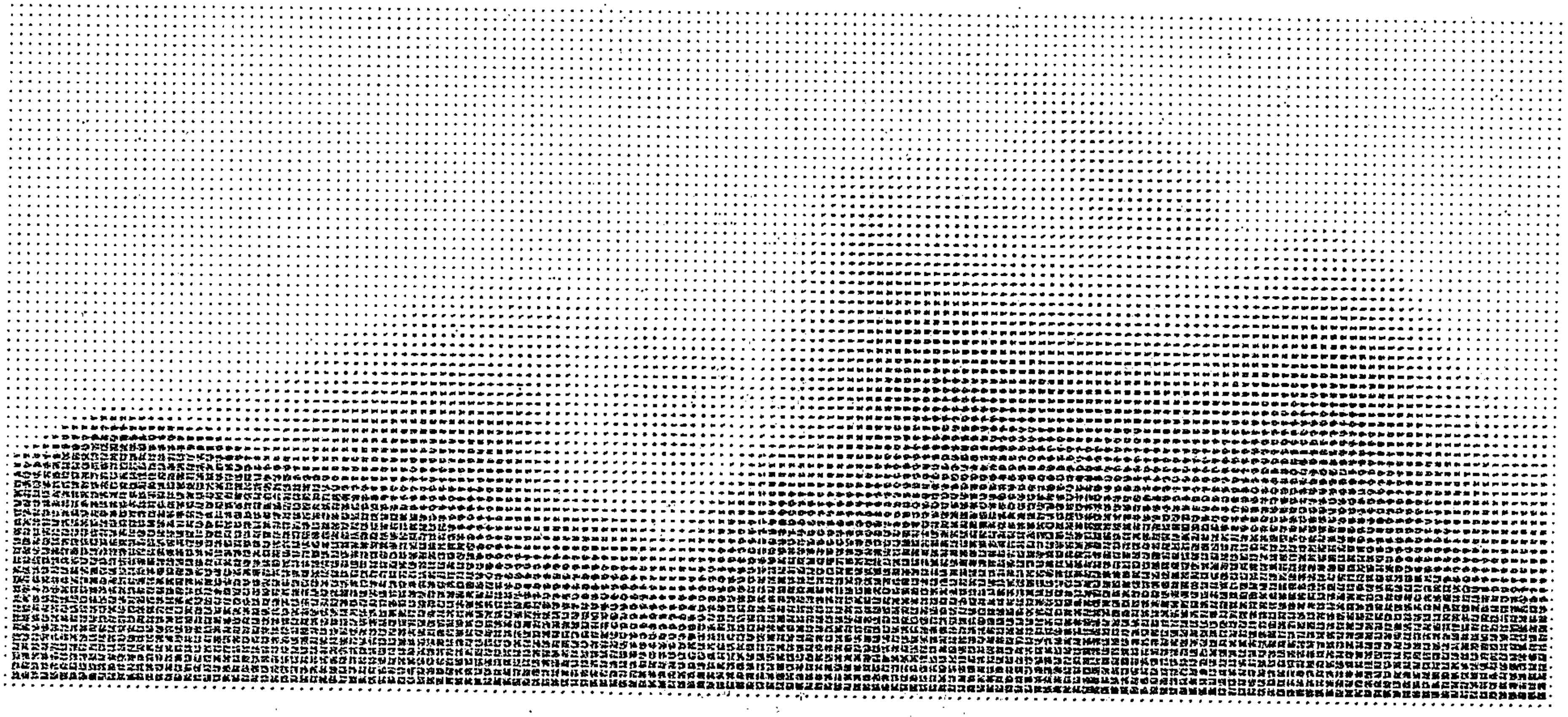


FIGURE 4: MAP OF BANK RESISTANCE FOR THE AREA SHOWN IN FIGURE 3, CALCULATED AS CUMULATIVE VALUES OF DHSS (SEE TEXT). THE DARKNESS OF EACH PIXEL IS INVERSELY PROPORTIONAL TO THE PROBABILITY THAT IT WILL BE ERODED

TABLE 1: Mean values for the heights above river level (at low flow) of terraces shown in Figure 3 and the shear strength of the alluvium at water level.

Terrace vegetation type	Mean Height (m)	Mean S.S. (kilopascals)
Unvegetated	0,5	10
Grassland	1,8	15
A. albida woodland	2,4	20
Riverine woodland	3,5	30
C. mopani woodland	4,9	80

It is not sufficient to use the D, H and SS values of a given pixel without consideration of these values for intervening pixels, between it and the active channel. A pixel of weak material will have a low probability of erosion if it is sited behind strong alluvium which must be removed before the weak pixel can be subject to erosive forces. Figure 4 is a map of cumulative values of H.SS, with the pixel length (50 metres) taken as a unit value of D. For each pixel, its own value of H.SS is added to that of its weakest neighbour (i.e. lowest cumulative DHSS). The technique does not assume that erosion proceeds in a direction perpendicular to the channel, but may be at an angle of up to forty five degrees, allowing erosion to skirt around obstacles.

Notice from Figure 4 how high banks with a high shear strength (e.g. the Mopani terrace) are resistant to erosion even when they are close to the active channel. Unvegetated sand on the other hand has low mean values of H and SS and constitutes a weak bank with a high probability of erosion. Notice how the abandoned meander near the centre of Figure 3 shows up as an arc of weakness on Figure 4.

THALWEG MOVEMENTS

It cannot be assumed that erosion is uniformly distributed across the width of the river, since flow is typically concentrated within a deep water channel, known as the thalweg. The probability of the bank being eroded must therefore depend on the location of the thalweg relative to the bank.

The plan form of large braided rivers tends to alternate between wide, shallow stretches with many islands and narrow deep stretches known as nodes (Chien, 1961; Coleman, 1969). Nodes tend to occur where the banks are particularly resistant to erosion and Nugent (1983) has identified five such points downstream of Kariba dam, where the Zambezi is controlled by rock which outcrops in or near the channel. Several more nodes are evident along alluvial stretches.

Coleman (1969) found that the wide stretches between nodes on the Brahmaputra river are associated with a high variability of current directions within the channel and that this in turn promotes rapid erosion of the banks, as the full force of the thalweg is periodically directed towards them. It is not possible to measure the range of current directions associated with the periods between successive images of the river. Nor is it relevant to measure the position of the thalweg relative to the bank since, although this is often visible on the aerial photographs, it may have moved several times between successive periods of photography.

Channel width is easily measured and can be used as a surrogate for flow variability and thalweg migration within the channel. The width of the channel has increased over the study period and its absolute value is not likely to be closely related to the probability of erosion. A more sensitive measure is relative width; that is the width at any given point divided by the mean river width at that time. Nodes thus have negative values, while the stretches between them come out positive.

TIME AND DISTANCE FROM KARIBA

The channel response below dams built on large rivers shows variation in time and space. Makkavayev (1972) and Chien (1985) describe how adjustments in channel morphology begin immediately below the dam and move progressively downstream. The final adjustment is greatest near the dam site and progressively less marked in a downstream direction, as unregulated tributaries add their influence and diminish the effects of impoundment. The effects of unregulated tributaries on the Zambezi are likely to be small, as these account for only 2 per cent of the catchment at Mupata gorge.

It is anticipated that time elapsed since impoundment (T) will exert a negative feedback control on the erosion process. That is, bank erosion associated with high values of T will occur at a reduced rate, as the final channel form is approached. On the other hand, very low T values will also be associated with little erosion because the effects of impoundment will not yet have reached the study area. Time since impoundment is therefore an unsatisfactory variable since it is intermediate values of T that are expected to be associated with the highest probabilities of bank erosion.

The critical time is the time at which the effect of the dam starts to influence the study reach. A realistic measure might therefore be the time elapsed since this hypothetical moment. Unfortunately this "starting time" is not known and in any case would vary with distance downstream. Since time and distance are intimately related, the model should ideally use the combination of these two variables that best represents the effects of impoundment. Once again, stepwise techniques are appropriate to find the form of the time/distance variable that best explains the observed incidence of erosion.

ADDITIONAL TERMS

The four variables discussed above describe the river's hydrology, bank resistance, thalweg migration and reaction to impoundment with more or less precision. They may appear to summarise those attributes of the river which exert the greatest control over riverbank erosion. One of the major advantages of a probabilistic model of this type is that it can be tested against the data. Additional terms can be added as independent variables and those that contribute little to the explanation of erosion can be dropped. The success of each combination of variables at describing probability of erosion can be assessed from the value of 'R', the multiple regression coefficient.

Examples of additional terms that should be tested in this way are suggested by the experience of other workers. Hooke (1979) found that the antecedant precipitation index (API) was the most important single factor in determining erosion on several streams in southwest Britain. API is a measure of the rainfall prior to a given flood event. It affects bank erosion because wetter bank alluvium is weaker and more prone to collapse.

Unlike Hooke (1979), this study does not consider individual storm events. A variable such as "total precipitation" should be considered as an alternative to API. This gross measure of the sum of all rainfall during the time period between sucessive photographic images might be more important as a crude estimate of streamflow from unguaged tributaries, than as an index of bank wetness.

Coleman (1969) found that the rate of rise and fall of river level is an important control on bank erosion. As groundwater re-enters the channel on the falling stage, lateral subaqueous flow of sediment may instigate shear and collapse of the overlying bank. Guy (1981) reports a similar phenomenon on the Zambezi following the abrupt closure of all six flood gates in 1966 "large blocks of bank fell into the river" (Guy, 1981, p208). The rate of rise and fall of river level, following flood gates being opened or closed, has probably remained fairly constant.

The total number of such fluctuations in level may have varied markedly and the effect should be tested as an additional term in the model. A suitable measure could be the number of flood gate closures during the period.

MANIPULATION OF DATA WITHIN THE MODEL

Once the variables have been formulated, it is found that each pixel-observation is represented by a unique set of conditions. The number of such observations is huge, being the product of the total number of pixels and the number of images less one. It is inappropriate to use each pixel-observation as a discrete case in the multiple regression equation, since the frequency of erosion associated with an individual picture element can only be either 0 or 1. That is, the pixel is either eroded or not eroded.

Some form of categorisation is necessary. The data must be put into size classes in order that frequencies of erosion can be related to those pixels falling within a range of physical conditions. If the classes are too small, then probability of erosion will be based on too small a sample to be accurate, generating random variation within the data set and resulting in low values of the multiple regression coefficient. At the other extreme, progressively larger classes contain progressively less information about the physical system and become of progressively less value as predictive tools.

The situation is illustrated in Table 2. The image shown in Figure 4 has been compared with the next image of the same area to establish the frequency with which pixels of various DHSS values were eroded. Figure 4 depicts the riverbank in 7214 picture elements, of which 1018 had been eroded (i.e. were represented as water) by the time of the next image. As expected, the pixels with low values of DHSS were eroded with a greater frequency than those associated with high values of DHSS.

Table 2 groups the pixels under four differant classification schemes. Table 2A uses a scheme in which DHSS values are grouped into classes which are five wide. That is, the first class includes all pixels with DHSS values from 0 to 5, the second class runs from 5 to 10 etc. In Table 2B the classes are twenty wide, so all the pixels from the first four classes of 2A fit into the first class of 2B. Classes of Table 2C are fifty wide and each class of Table 2D spans 200 units of DHSS.

The probability of pixels being eroded is substituted for the frequency with which each class of pixel was eroded. Thus in Table 2A 114 pixels have DHSS values less than 5, of which 74 were eroded. The probability of erosion associated with this class is thus 74/114 = 65%.

TABLE 2: Probability of erosion associated with pixels of various values of bank resistance (accumulated DHSS, see text). Class width = the range of values of accumulated DHSS held within each class.

(A) CLASS WIDTH = 5

D	P	D	P	D	P	D	P	D	P
1	65	26	50	51	40	76	29	101	0
2	83	27	50	52	42	77	9	102	13
3	73	28	54	53	10	78	17	103	9
4	73	29	29	54	22	79	6	104	0
5	45	30	58	55	47	80	30	105	0
6	73	31	59	56	18	81	10	106	3
7	68	32	59	57	22	82	4	107	0
8	59	33	52	58	11	83	0	108	0
9	65	34	34	59	13	84	10	109	0
10	31	35	58	60	14	85	11	110	0
11	74	36	68	61	31	86	25	111	0
12	59	37	44	62	14	87	0	112	0
13	71	38	46	63	6	88	14	113	0
14	57	39	23	64	14	89	0	114	0
15	37	40	52	65	14	90	10	115	0
16	52	41	44	66	33	91	0	116	0
17	70	42	59	67	38	92	3	117	0
18	58	43	31	68	6	93	20	118	0
19	64	44	18	69	22	94	0	119	0
20	38	45	46	70	20	95	0	120	0
21	59	46	50	71	18	96	22	121	0
22	64	47	44	72	97	97	0	122	0
23	61	48	35	73	2	98	0	123	0
24	59	49	13	74	33	99	11	124	0
25	36	50	36	75	11	100	0	125	0

(B) CLASS WIDTH = 20

D	P	D	P
1	71	26	3
2	58	27	2
3	58	28	0
4	49	29	0
5	56	30	0
6	61	31	0
7	44	32	0
8	47	33	0
9	49	34	0
10	38	35	0
11	32	36	0
12	45	37	0
13	28	38	0
14	19	39	0
15	14	40	0
16	11	41	0
17	16	42	0
18	15	43	0
19	12	44	0
20	12	45	0
21	6	46	0
22	7	47	0
23	3	48	0
24	10	49	0
25	2	50	0

(C) CLASS WIDTH = 50

D	P
1	62
2	55
3	48
4	47
5	33
6	22
7	14
8	12
9	6
10	4
11	2
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0

(D) CLASS WIDTH = 200

D	P
1	54
2	21
3	3
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0

D = Division Number, P = Probability of erosion %

The probability of erosion is calculated in this way for each class, under the four classification schemes.

Inspection of Table 2 shows that classification schemes involving many small classes yield probabilities which fluctuate wildly. For instance class No.96 in Table 2A, pixels with DHSS values between 475 and 480, has a probability of erosion of 22%. Yet the two classes either side are associated with zero probability of erosion. This variation occurs because class No.96 holds only nine pixels, two of which were eroded. None of the pixels in adjoining classes were eroded. Accurate probabilities cannot be based on such a small number of cases. The solution is either to make the pixels smaller (less than 50 metres square) or to make the classes bigger, so that each class encompasses a large number of pixels.

Tables 2B, 2C and 2D show the effect of an increase in the size of each class. Table 2D, in which the class interval spans the greatest range of DHSS values, provides a very accurate estimate of the probability of erosion since each probability is calculated from a large number of cases. Because it applies to a wide range of riverbank conditions however, the probabilities say little about the effects of variation in bank resistance and thus have little predictive value. The most satisfactory of the classification schemes illustrated in Table 2 appears to be that of 2C, with a class interval of fifty. Probability of erosion within this classification scheme can be seen to diminish consistently, although irregularly, to divide the DHSS values into eleven classes.

The classification scheme adopted for the bank resistance variable in Table 2C generates probabilities associated with eleven categories of bank resistance for inclusion in the multiple regression equation. The maximum number of cases that will be analysed will thus be eleven multiplied by the number of width classes represented within the image and this multiplied by the number of classes of the time/distance variable present. With the addition of each new variable the total number of classes is increased and the number of pixels within each class is reduced, thus the accuracy of the calculated frequencies is reduced and the multiple correlation coefficient is reduced. The structure of the model thus affects the accuracy of the result.

All the independent variables with the exception of the hydrological variable will be divided into classes. The classification scheme adopted for the model should be determined using two considerations:

1. The total number of classes used is directly related to the range of variation expressed by the independent variables but inversely related to the accuracy with which frequencies of erosion are determined.

2. The distribution of classes between the independent variables should reflect the influence each of the variables exerts on probability of erosion.

USING THE MODEL PREDICTIVELY

Having found an optimum form and classification interval for the variables, the complete data set is included in a single multiple regression equation. The form of the equation obviously depends on which variables were found to be significant and were included in the analysis. Take the case in which four independent variables are used: a hydrological variable (H), a bank resistance variable (BR), a channel width variable (W) and a time and distance variable (TD). The final equation thus becomes:

$$P = a \cdot H^{b1} \cdot BR^{b2} \cdot W^{b3} \cdot TD^{b4}$$

Running the data set in a multiple regression yields values for the constant (a) and exponents (b1 to b4).

The next stage is to test the model to find out whether the equation accurately predicts bank erosion. The test must involve data not used in the model's formulation. If the model were applied to the data set that generated it, then it would certainly appear to predict bank erosion with great accuracy. It must be shown that the relationship expressed by the regression equation is general enough to apply to other stretches of the Zambezi or at times other than those already considered.

Since there are a limited number of periods from which images are available to formulate the model, keeping one or two aside for testing purposes would reduce the accuracy of the final product. It is therefore appropriate to test the model using periods of photography already considered but on stretches of river not already used.

The testing process involves finding the values for all the independent variables for each pixel of the test image. For each pixel a probability of erosion is calculated using the regression equation. These probabilities are then compared with observed frequencies of erosion calculated by comparison with the next image, as described above.

Assuming that the tests are successful and the regression equation is able to predict the frequency of erosion with acceptable accuracy, the model is now at a stage where it can be used to predict future bank erosion. The values of all the independent variables are known, with the exception of the hydrological variable. It is not practicable to predict the future flow regime of the Zambezi. Probability of erosion must be estimated for various possible conditions of future flow.

By substituting hypothetical flow regimes into the hydrological variable and using known values of the other independant variables, probabilities of erosion are calculated using the regression equation. The product will be a set of maps showing the probabilities of erosion under various flow conditions. By substituting frequency for probability, the amount of *A. albida* expected to be lost in the future can be calculated in terms of the streamflow expected to be released along the river.

FUTURE DEVELOPMENTS

Extensions to this model could improve it quantitatively, by improving the accuracy with which it predicts erosion or qualitatively, by enabling it to predict change of other aspects of channel morphology. A qualitative extension of the model could be effected by setting up several regression equations, each structured to find the relationship between the causative elements and different aspect of channel change. The equations would then be solved individually or simultaneously (where they are inter-related) to predict the complex response of a river channel to a particular set of natural conditions or the work of man.

Quantitative improvements could be made by representing the independent variables by more pertinant measures. For instance, the hydrological variable could be formulated using a sediment transport equation to represent the volume of sediment carried by each discharge, rather than using the discharges themselves. It would not detract from the model to use deterministic measures such as this since the optimum structure is found iteratively using stepwise techniques. Used in this way, the model is not an alternative to deterministic methods but a new framework within which such methods can be applied.

CONCLUSIONS

The model represents a radical departure from standard techniques for predicting river channel changes. By considering variation in a single degree of freedom (river-bank erosion), the model has the advantage of simplicity. By using historical data to establish a statistical relationship between bank erosion and the causative elements of the physical system, the model is able to consider the unique response of an individual river. Finally, by using established fluvial theory only to determine the form of the independent variables and testing these variables using stepwise techniques, the model avoids the inaccuracies arising from our imperfect knowledge of fluvial processes.

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