AGGRADATION AND DEGRADATION PROCESSES IN A HUMID TROPIC FLUVIAL SYSTEM, BENIN CITY: IMPLICATIONS FOR MANAGEMENT

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Abstract

Volumes of erosional (degradation) and depositional (aggradation) sediments were estimated by reconnaissance methods using the power function model as an analytical tool in an agricultural basin, Rdo State, to examine what insight might be gained into the sediment budget in the absence of direct measurement. Results reveal that rates of aggradation and degradation are non-linear. The results also reveal that aggradation is higher than degradation which suggest that the river is in its maturity stage. Lie implications for management is evaluated for channel stability, sand mining and navigation.

Introduction

Landscapes are fascinating features. Since about 1950, the emphasis on better understanding of geomorphic processes of erosion and deposition and the many aspects of systems theory permit preliminary appraisals of important questions about changes in the landscape around us. Earth scientists now address questions about erosion and deposition that are important both for academic and applied reasons. For example, those curious about the world around them should be interested in such question as, how sensitive to changes in running water are the processes of erosion and deposition?

Much has been written about aggradation and degradation as an aspect of climatic fluvial geomorphology from the viewpoint of how landforms vary with worldwide climatic zones (Budel, 1981; Derbyshire, 1973, 1976; Peltier, 1950; Stoddart, 1969;- Tricart, 1974; Tricart and Cailleux, 1972). Changes imposed on a fluvial system, be they natural or man-induced, tend to be absorbed by the system through a series of channel adjustments (Gilbert, 1880; Mackin, 1948; Lane, 1955; Hack, 1960; Schumm, 1973; Bull, 1979, 1991; Simon, 1988). These series of channel adjustments also known, as negative feedbacks are super imposed on a series of shifting environmental conditions (Aziegbe, 2003), that is predicated on time scale (Thornes and Brunsden, 1977). In other words, changes in environmental conditions controlling the fluvial systems brought about by agricultural practices, has resulted into drastic changes in energy condition.

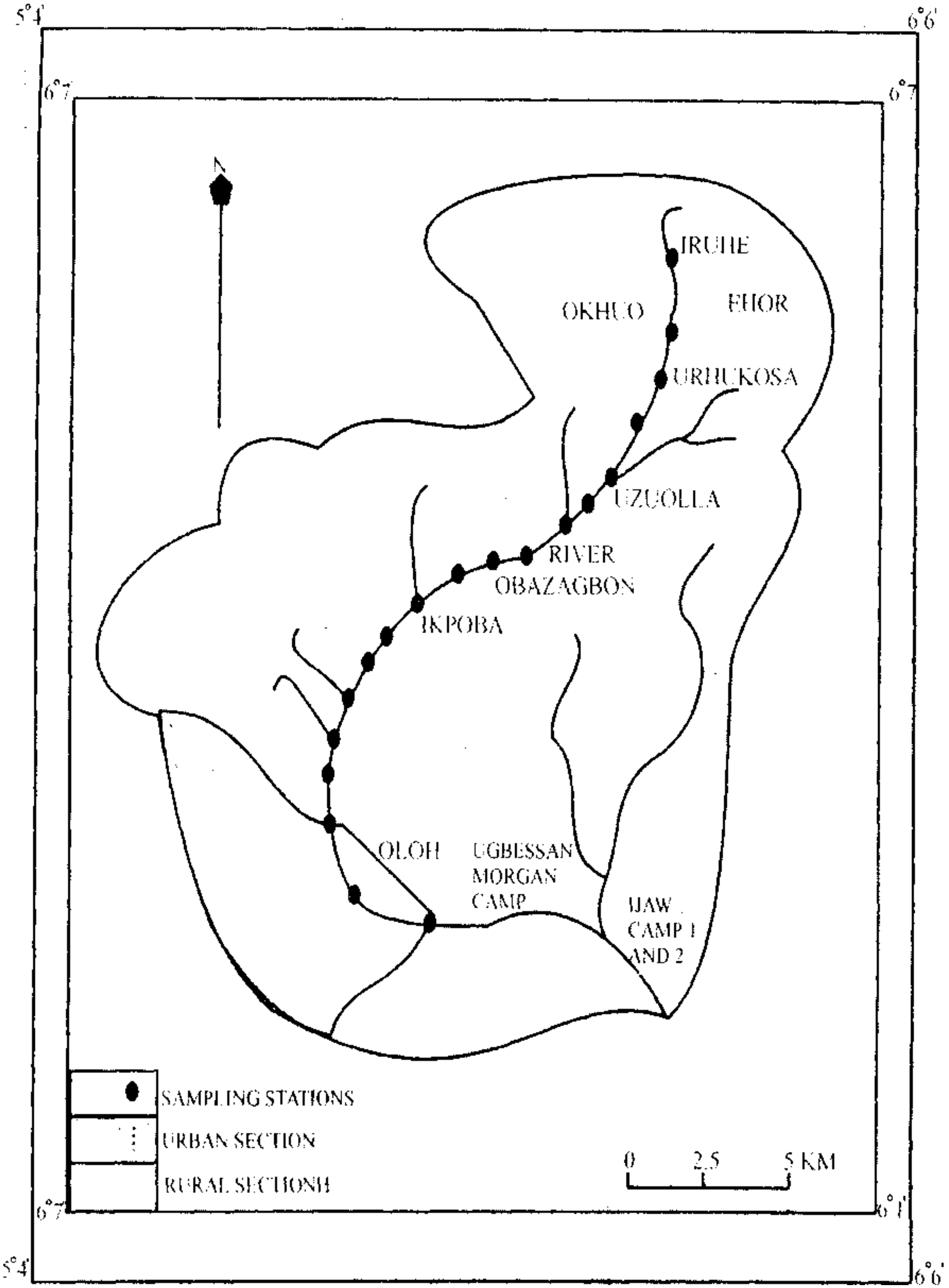


FIG. 1.1. IK FOB A RIVRR BASIN SHOWING SAMPLING STATIONS

This has lead to a rejuvenated condition in the fluvial system much like that imposed by dredging, enlarging or straightening or a natural lowering of base level. Drastic changes in energy conditions will in turn bring about sudden and significant shock to fluvial system that causes both erosion (degradation) and deposition (aggradation) and other observable morphologic changes. In this study, aggradation is seen as a disequilibrium mode of operation that raises the altitude of a reach of an active stream channel by depositing bedload while degradation is the disequilibrium mode of operation that lowers the altitude of a reach of a stream by removing bedload and eroding channel bed. The sand-bed stream channels of the Ikpoba River basin provide an opportunity to investigate

Geography of the Studied Basin

The Ikpoba River Basin is located between latitudes 6° 1^1 and 6° 7^1 North and longitudes 5" 4^1 and 6^U 1^1 Hast (Fig. 1.1). The studied basin drains an area of 520.3km^2, and it is a third order basin. A river distance of 25km was considered for a detailed investigation in this study.

Theoretical Consideration

Majorly, five principal mathematical functions [$f(X_1Y)$] are commonly used to express functional relationships among independent (X) and dependent (Y) variables in fluvial erosion research. They are: **Linear,** Y = ax b; **Logarithmic,** Y = a/nX + b, where /n is the natural logarithm; **Exponential,** $Y = ae^{bx}$ where 'e' is the naperian logarithm; **Polynomial,** $Y = a+bX+eX^2 + -$

---- $+ MX^{in}$; and **Power.** $Y = ax^b$. This present study considers the power function model.
The general form of the power function model is;

$$E = a(t)^b \text{ -- } (1.1)$$

Where: **E** = elevation to the bed for a given year in metres, **a** = coefficient determined by regression, representing the pre-disturbed elevation of the bed, in metres above sea level, t = time since the beginning of adjustment process, in years, w here **t„ = 1;** and, **b** = dimensionless exponent, determined by regression and indicative of non-linear rate of change on the bed. Trends of bed-level change through time at gauging stations served to support the well-known concept of non-linear adjustment. Once it was established that power functions provide the best fit to these gauge data, data from periodical!) surveyed sites were similarly fitted. Both exponential and power equations were initially fitted to observed data set. However, the power function gave consistently superior matches of the empirical data, and was therefore used to describe bed-level adjustment through time.

It follows that when equation 1.1 becomes asymptotic; that is, **a > 1** aggradation is taking place. But when **a<l** degradation results. In the same reasoning, when the equation becomes asymptotic, that is. **b>0,** it is degradation and, **b<0** is aggradation.

Justification for the Use of Power Function as an Analytical Tool

The power function is widely used in geomorphic studies because of its statistically significant fit to most data; its simplicity , and its relative ease of interpretation (Bull 1991:27). The power function provides consistent better fit to empirical data than an exponential function (Simon and Hupp 1992). Power functions describe orderly changes in geomorphic systems particularly when analyzing process behaviour (Wilson and Benneth, 1976:61). Interpretation of power function equations involves comparison of both exponents for regressions of different slope and coefficients of regression of similar slope. The interpretations of the equations are alometric when analyses are made from a dynamic or static view point (Bull 1991:27) in that case, it becomes:

$$Y = aX^b$$

Where: Y = a dependent variable
X = an independent variable
and **a** and **b** are constants

power function models describe the rate of change of part of a system as compared to the rate of change of another part of the same system or to the rate of change for the system as a whole (Woldenberg 1968; Faulkner 1974; Bull 1975; Graf 1982a). And because the study reported here investigated the rate of change of part of a system as compared to the rate of another part of the same system the power function model was used as an analytical tool. The power function model is a special case of non-linear model and it implies that some or all of the mathematical parameters employed in the description of the system operation are not identical over all magnitudes and regimes of system operation. In other words, they are free, within certain limits, to change their values in harmony with changes in the system variables. Unlike the linear model, they don't always satisfy the principle of superimposition (i.e. the addition or subtraction of subsystem outputs to produce a total system response). Thus, a nonlinear system cannot be accurately described by linear algebraic or linear differential equations (Bennett and Chorley, 1978). The nonlinear system will not exhibit simple proportionality between the amplitudes of input and output, and will generate in the output not only the frequencies contained in the input but new frequencies related to these (Kisiel, 1969).

Unlike the linear model also, they exhibit multiple steady states which make their behaviour indeterminate and to some degree, unpredictable (Bennett and Chorley 1978). These two qualities (indeterminacy and unpredictability) make the power functions model particularly suitable for fluvial investigation whose response to modification cannot be predicted (Schumm, 1985a).

Materials and Method

Channel-bed elevation was determined in line with Blench (1973) model. According to Blench (1973), the average annual water-surface elevation at a given low-flow discharge can be used to infer an average annual channel-bed level by assuming that changes in water surface elevation at that discharge are caused by bed level change. The technique was used at gauge sites to determine average annual changes in channel-bed level because historic bed-elevation data were not available.

Volumetric changes in channel were computed by comparing cross-section over the length of the stream for different time period. This method allows estimates of the volume of material eroded or deposited to be made. This is so because variations in channel forming processes during fluvial adjustment cause changes in channel area and morphology through the removal or deposition of material (Simon and Hupp, 1992; Brush, 1961; Costa and Baker, 1981). In this study, measured cross-sections provided primary database for documenting changes in channel area and volume. For each cross-section measured at bankfull, channel area, mean depth and width were digitized, calculated, and plotted by river kilometre for each time period. Rhoads (1988) and Simon and Hupp (1992) provide information on the digitizing technique. At each station, channel bank full cross- sectional area was determined, file method consisted of dividing the. cross-sectional length into segments of one metre from a tagged measured cable. The bankfull depth at each tagged segments is the vertical distance between the bed surface and the cable at the top. Where water surface depth was required, the depth was measured to the water surface from the bed surface. And because cross- sectional data were obtained from a variety of sources, direct section-to-section comparisons were not always possible. Instead a tend line was visually fitted through the data and was used to represent values of a given parameter over the length of the stream, and for the specified period. Simon and Hupp (1992) had previously used this method and they recommended it for fluvial studies.

By overlaying the plots for the specific feature and by digitizing the area between the trend lines, estimates could be made of changes in that feature due to adjustment processes acting between the data of initial adjustment and the present data. Another way of computing volumetric changes in channel size at shallow reaches was to integrate depth changes at a site over the stream length studied. This provided information regarding the amount of vertical change in metre square. When multiplied by the bottom width, the volume of material eroded or deposited from the channel-bed by fluvial processes can be determined. Both methods were adopted in this study but the first method yielded moderate data values, and was therefore preferred.

Since changes in channel width generally occur after significant incision, Simon and Hupp (1992) recommended that a constant bottom width be used to estimate volume of material eroded by degradation. Similarly, plots of width changes provide data (in metres square) that is multiplied by bank height to calculate volumes eroded from channel banks by mass wasting processes (Hook 1978; Thorne 1984; Thorne and Biedenharn 1983; Simon and Hupp 1992). Plots of these changes in total channel area represent total volume of sediment eroded or deposited in channel.

Results and Interpretations

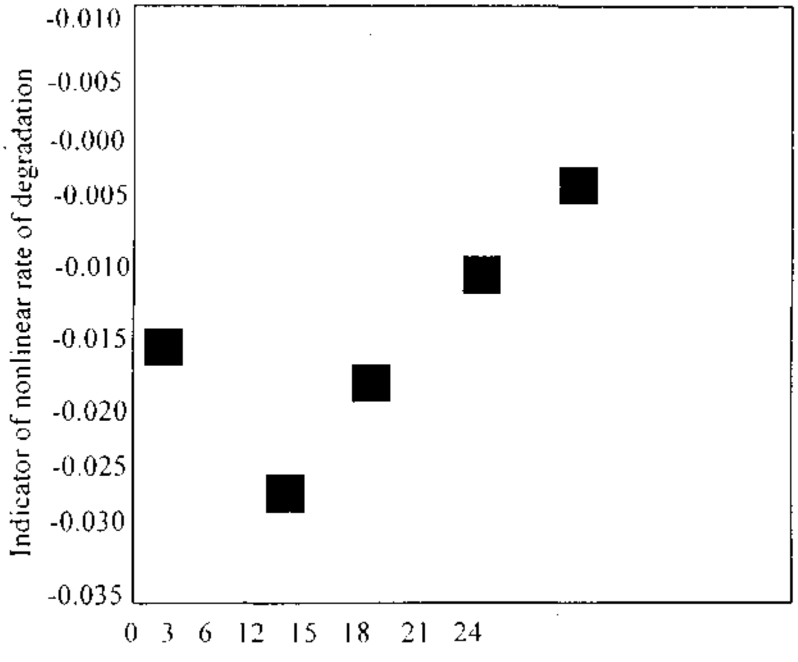
Channel recovery involves geomorphic. hydraulic, geotectnic and hydrologic processes that need to be considered in concert to understand the fluvial system. Changes in one aspect of a fluvial system (for example, bed degradation) can affect other aspects of the system (such as bank stability). Generally, changes in channel gradient or stream energy (caused by channel modifies"' cause a shift to non-equilibrium conditions and the initiation of adjustment processes such as degradation and aggradation.

Some of the most rapid and dramatic adjustments that take place along an alluvial channel occur on the channel bed. Channel-bed degradation and aggradation are important processes by which a channel adjusts towards its premodified energy level.

Aggradation and Degradation

Channel bed-level adjustments are described over time, at a site, by parameter “b” (in equation 1, $E = at^{1}$’), which represents the non-linear rate of change on the bed. A list of calculated b- values for studied sites is given in fable 1.1. In using b-values to calculate channel bed-level changes, one must keep in mind that “t„ = 1" represents the year before the particular channel-bed process become active at the site, and not necessarily the time at which channel disturbance started. When plotted by river kilometre, b-values consistently show the attenuation of degradation process with increasing distance upstream (Fig. 1.2).

An important point in the extrapolation of channel-bed level changes through time is the nature of the parameter “b” and because “b” represents a non-linear rate of change v,. mil decreases with time (Fig. 1.3), the assumption is that rates of aggradation and degradation are in fact time based. Extrapolation into the future is of course uncertain (Simon, 1990).



Distance upstream from mouth
Fig. 1.2. Indicator of nonlinear rate of degradation (b) and river kilometer for sites 1,5,10,15,and 20

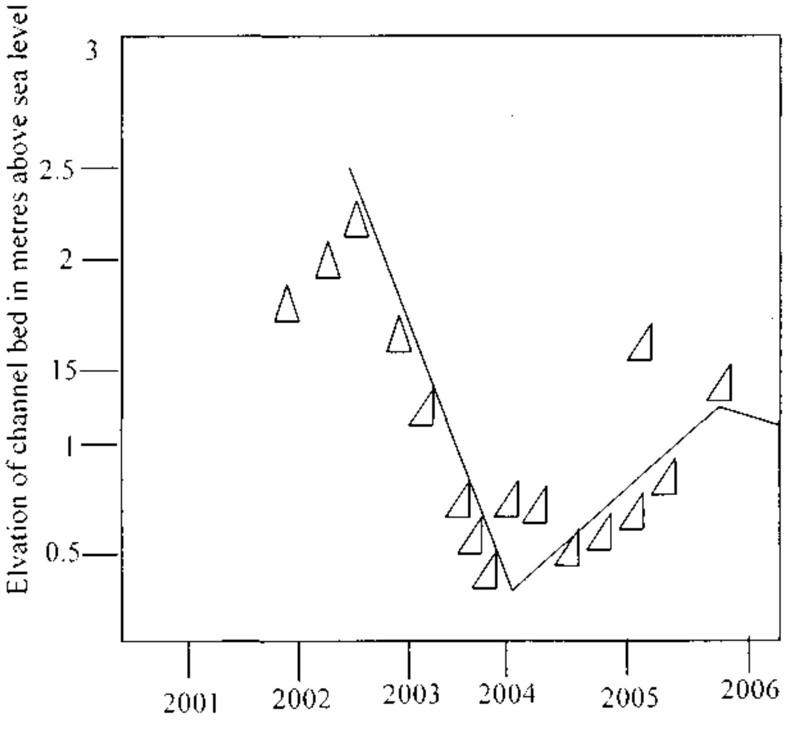


Fig. 1.3 Relation of channel-bed elevation and time since channel disturbance for site 10, river km 10.1 (curve is visually fitted).

Table 1.1 Indicator of Nonlinear Rates of Aggradation and Degradation (b-values)

Station Number	B	n	r^2	RK	t_o
20	-0.00989	15	0.9	20.2	2001
19	-0.00930	15	0.9	19.3	2001
18	-0.00560	15	0.6	18.2	2001
17	-0.01160	15	0.8	17.4	2001
16	-0.01430	16	0.9	16.8	2001
15	-0.01660	16	0.8	15.2	2001
14	-0.01540	18	0.8	14.3	2001
13	-0.01620	18	0.9	13.2	2001
12	-0.02020	18	0.7	12.4	2001
! 1	-0.02330	19	0.8	11.6	2001
10	-0.02300	19	0.7	10.1	2002
9	-0.02470	19	0.9	9.3	2002
8	-0.02210	19	0.8	8.0	2002
7	-0.03140	10	0.7	7.0	2002
6	-0.03093	10	0.6	6.1	2002
5	-0.02960	10	0.9	5.4	2002
4	-0.02860	15	0.8	4.0	2002
īt	-0.02780	15	0.5	3.2	2002
2	-0.2730	13	0.5	2.0	2002
i	-0.01660	10	0.9	1.5	2002

b indicator of nonlinear gradation rate; **n** = number of observation; r^2 = coefficient of determination; **RK** = river kilometre; **t„** = year prior to beginning of gradation process.

NOTE: b-values column is calculated from equation **1** $(E = a (t)^b)$.

Source: Compute:' result of fieldwork data.

. However, the nonlinear attenuation of the degradation process with distance at a site through time, accounts for much of the inherent variability with time.

Degradation

Projected amounts of channel bed-level lowering through time by degradation were calculated by solving equation 1 at 5 year period (that is, from 2001 to 2006 (Table 1.2). These projections should be treated with caution because of limited time frame of the data analysed. However, for the purpose of this study, estimates of long-term-channel geometry are based on a 5 years degradation period in accordance with the calculated b-values (Table 1.1).

The presentation of data derived from b-value in this fashion displays the time-based reduction in degradation (distance between successive curves in Figure 1.4a, and the asymptotic nature of curve in Figure 1.3. And because of'the relatively homogenous channel-bed sediments along the stream, significant variations from the generally smooth asymptotic shape of the curves (Fig. 1 4b.) can be attributed to the delivery of large amounts of bed material from channel disturbance.

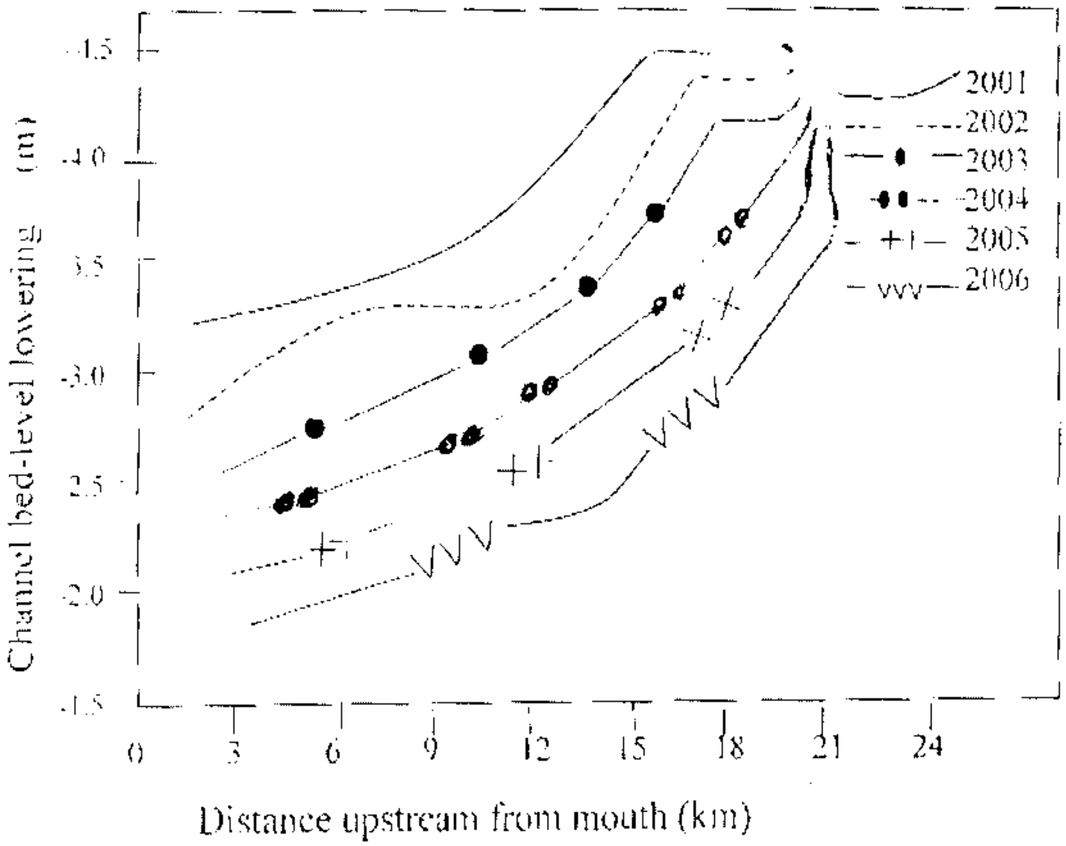


Fig. 1.4.(a). Projected channel bed-level lowering

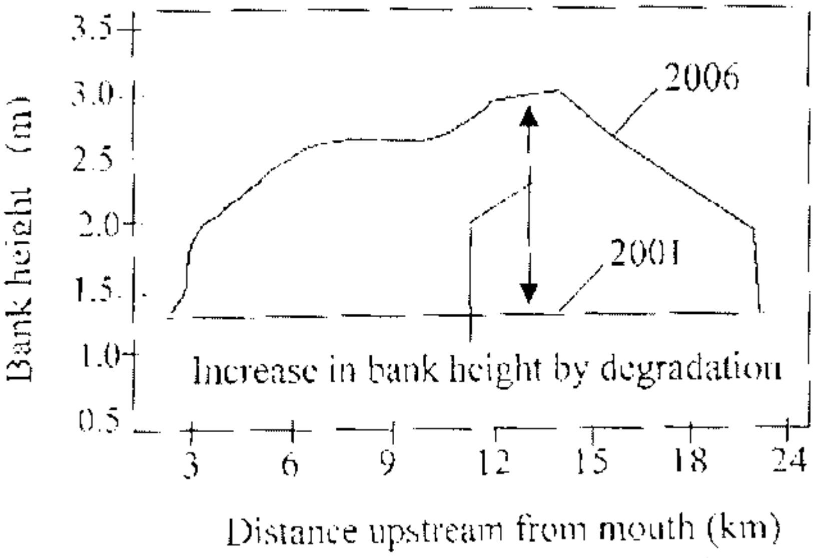


Fig. 1.4.(b). Changes in bank height by degradation (2001 2006)

Table 1.2 Calculated Amounts of Channel-Bed Degradation at 1-Year Intervals to the Year 2006. (. no data)

Station Number	River Kilometer	2001	2002	2003	2004	2005	2006
1.	1.5	-	-3.05	-4.07	-4.70	-5.15	-5.51
2. .	2.0	-	-6.35	-8.46	-9.75	-10.69	-1 1.42
3.	3.2	-	-7.16	-9.53	-10.99	-12.04	-12.86
4.	4.0	-	-1 1.94	-15.85	-18.24	-19.96	-21.29
5.	5.4	-	-12.26	-16.28	-18.72	-20.48	-21.86
6.	6.1	-	-13.03	-17.29	-19.89	-21.76	-23.21
7.	7.0	-	-13.60	-18.03	-20.73	-22.68	-24.20
8.	8.0	-	-14.48	-19.20	-22.07	-24.14	-25.74
9.	9.3	-	-14.90	-19.75	-22.70	-24.83	-26.48
10.	10.1	-	-10.76	-14.31	-16.48	-18.04	-19.26
11.	11.6	-	-12.24	-16.26	-18.72	-20.49	-21.87
12.	12.4	-	-11.43	-15.91	-17.49	-19.15	-20.44
13.	13.2	-	-1 1.47	-15.25	-17.55	-19.22	-20.51
14.	14.3	-	-10.33	-13.74	-15.82	-17.33	-18.50
15.	15.2	-	-8.37	-1 1.14	-12.84	-14.07	-15.03
16.	16.8	-	-8.06	-10.74	-12.38	-13.58	-14.50
17.	17.4	-	-885	-1 1.79	-13.59	-14.89	-15.91
18.	18.2	-	-7.76	-10.34	-11.93	-13.07	-13.97
19.	19.3	-	-5.80	-7.74	-8.93	-9.79	-10.47
20.	20.2	-	-7.24	-9.00	-13.12	-14.56	-15.56

Source: Computer result of fieldwork data.

Plots of channel profiles for various time periods that were overlain on each other were used to calculate the volumes of materials eroded from the channel bed (using a constant bottom width of 4.5 metres). A value of 10.2Mm^3 (Million cubic metre) was eroded during the study period (Table 1.5). Erosion along the stream course was not uniform. For example, station 11 recorded the highest channel-bed lowering. This large difference in channel-bed degradation is a function of three variables that control the response of alluvial streams:

1. The magnitude of the imposed disturbance;
2. The credibility of the channel bed; and
3. The presence/absence of coarse particle sizes (sand) for aggradation.

Table 1.5 Volume of Channel-Bed Material Eroded *by* Degradation

Stream	Volume (million of cubic metre)	
	Total	Per m^2 of Drainage Area
Ikpoba river (All Sites)	10.2	CO

Source: Computer result of fieldwork data.

Ikpoba river basin is both intensively and extensively farmed, and this represents imposed disturbance. In addition, the stream is susceptible to degradation due to the nature of sediment load. The stream is therefore extremely “sensitive” to changes in controlling variables such as gradient or velocity.

Upstream limits of present (2004) degradation can be obtained by noting the river kilometre at which the predisturbed trend lines meet the 2004 trend lines (Fig. 1.4a). The channel length affected by degradation was obtained by subtracting the river kilometre location of the area of maximum disturbance (AMD) from this upstream limit. When divided by the number of years since the channel was modified, it gives an average rate of upstream migration of the degradation process. This value can be used to estimate the location of knickpoints and expected degradation in years to come, assuming the degradation process continues to migrate at the same rate, and there is no further disruption of the channel.

Table 1.6 Upstream Limit of Channel-Bed Degradation and Rate of Headward Migration of Knickpoints (2004)

(AMD = Area of Maximum Disturbance)

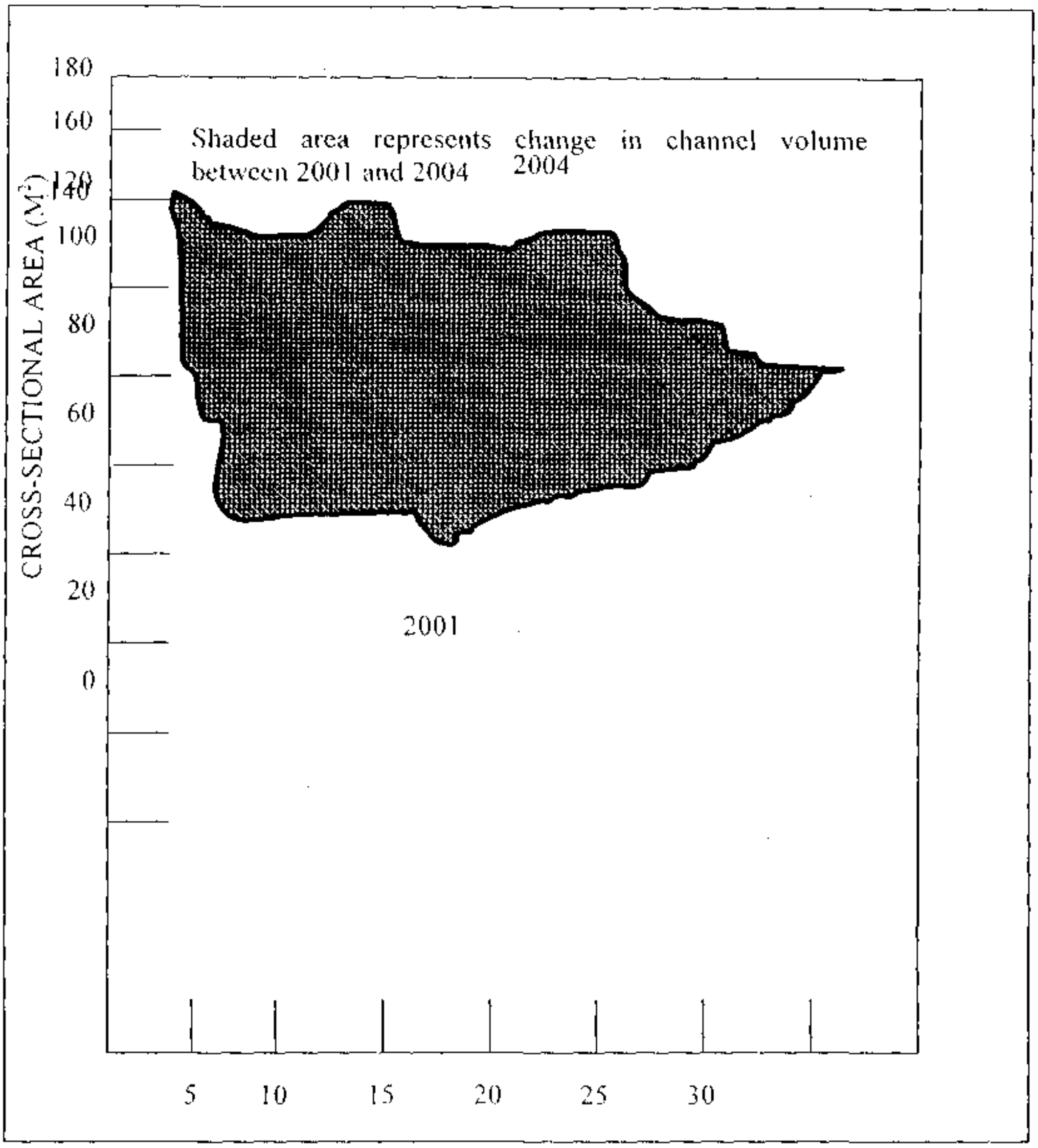
Stream	Location of AMD (river km)	Year Channel disturbance was observed and noted	Upstream limit of degradation (river km)	Rate of headward migration (km per year)
Ikpoba river	11.6	1999	20.2	1,33

Source: Computer result of fieldwork data.

Aggradation

Channel-bed aggradation and bank accretion are important attributes of adjusting fluvial systems. Aggradation reduces bank heights and aitls in bank restabilization. Besides, it also reduces channel capacity and consetpicntly, stream power by causing successive lower discharge flows to spread over the Hood plain and dissipate stream energy. In general, aggradation occurs at a site downstream the area of maximum disturbance (AMD), and just upstream from the AMD. Aggradation also occurs at low rates along reaches well upstream of the migratory degradation process because of “natural’’ fluvial processes and land-use practices commonly associated with the basin.

Projected amounts of aggradation calculated from empirical data for all sites up to the year 2006 range from 0.3m to 9.7 metres (fable 1.7).



DISTANCE UPSTREAM FROM MOUTH (KM)

Fig. 1.5 Changes in channel volume using cross-sectional area data at site 10.

Maximum values occur on the downstream stations. The lowest values of projected aggradation occur along the relatively undisturbed sites. For example, compare sites 1 — 5 with 10 — 20.

Table 1.7 Calculated Amounts of Channel-Bed Aggradation at 1-Year Intervals to the Year 2006. (Estimates Start at Different Times Due to Timing of Adjustment Process at a Site; - = Not. Applicable)

Year

Station No.	River km	2001	2002	2003	2004	2005	2006
1.	1.5	-	-	-	1.54	2.21	2.60
2	2.0	-	0.83	1.57	1.94	2.19	2.38
3.	3.2	-	-	-	1.66	4.70	6.01
4.	4.0	-	0.28	0.78	1.00	1.14	1.25
5.	5.4	-	1.16	1.84	2.21	2.47	2.67
6.	6.1	-	-	0.89	2.51	3.21	3.66
7.	7.0	-	0.67	3.17	3.58	3.89	4.13
8.	8.0	-	4.13	3.79	4.17	4.46	4.71
9.	9.3	-	2.57	3.17	3.58	3.89	4.13
10.	10.1	-	3.28	3.79	4.17	4.46	4.71
11.	1 1.6	-	0.96	1.29	1.49	1.64	1.75
12.	12.4	-	-	-	1.46	2.31	2.78
13.	13.2	-	-	0.84	2.36	3.01	3.44
14.	14.3	-	1.91	5.42	6.94	7.93	8.66
15.	15.2	-	0.16	0.22	0.25	0.27	0.29
16.	16.8	-	0.32	0.89	1.13	1.29	1.41
17.	17.4	-	-	-	2.65	3.55	4.1 1
18.	18.2	-	1.21	4.33	6.1 1	8.64	9.73
19.	19.3	-	1.33	3.66	4.10	5.11	8.97
20.	20.2	-	0.32	2.61	4.33	5.31	6.41

Source: Computer result of fieldwork data.

The volumes of sediment (generally tine and medium sand) deposited by channel-bed aggradation and bank accretion were calculated from plots showing changes of channel cross- sectional area over the stream length (Fig. 1.5). Volume of deposition for all sites amounted to 13.9 Mm^3 (Million cubic metre, Table 1.8). This value, averaged over 20.2 river kilometre and using an average bottom width of 4.5 metres represents approximately 2.5 metre of channel bed-level recovery throughout the Ikpoba river from 2001-2006. If the river channels undergo significant and widespread degradation that exceeds the observed values, a long period of instability is expected. Like the degradation process that migrates upstream to reduce channel gradients, aggradation also migrates upstream, but in this case, to cause subsequent increase in channel gradients. This type of oscillatory response is reported by Scluimm (1973) and Alexander (1981), and is discussed in detail by Simon (1992). Gradient reduction at a site after years of down cutting decreases stream power to such extent that the available stream power is insufficient to

Table 1.8 Volume of Sediment Deposited by Aggradation and Accretion from Disturbance to 1999

River	Deposited Volume (Mm^3)	Percent of Total Eroded	Starting Data
Ikpoba river (All Sites)	13.9	20.8	1996

Source: Computer result of fieldwork data.

transport increased sediment loads emanating from newly eroding upstream reaches. The result is a trend ot general aggradation that migrates headward from area ot maximum disturbance (AMD). This mildly increases gradient, and thereby increases the capability of the stream to transport its bed load (Figure 1.6 a and b).

Implications for Management

The implications for aggradation and degradation from the viewpoint of environmental management include bank stability, sand mining and navigation.

Bank Stability

The sand-bed reach studied presents a range of management problems. Most obvious is the question of land protection against the dominantly lateral erosion that is intrinsic in the sand transfer processes. Agricultural lands border the river channels and, elsewhere, estate properties are exposed. The conventional solution to erosion attack is heavy revetment. But consideration of the underlying process of sand transfer in the reach shows that it can at best displace the problem to another site. If the river is unable to perform lateral erosion to a growing bar, it will flow faster and deeper through the constricted reach and perform its sediment exchange some distance downstream. In any event, experience has taught that bank protection in the face of direct attack by the river is exceedingly difficult and expensive. It will be more effective to recognize the room required by the river to function in its habitual way, to use knowledge about the riverine processes to anticipate unfavourable changes, and then to use guide works to encourage the river into a modified course of development that nevertheless, preserves its freedom of erosion and deposition. The channel zone between the setback Hood dikes, which are at least a kilometre, and frequently considerably more, certainly provide that room. But this strategy unquestionably ends in recommendation than implementation in the face of plans for land development.

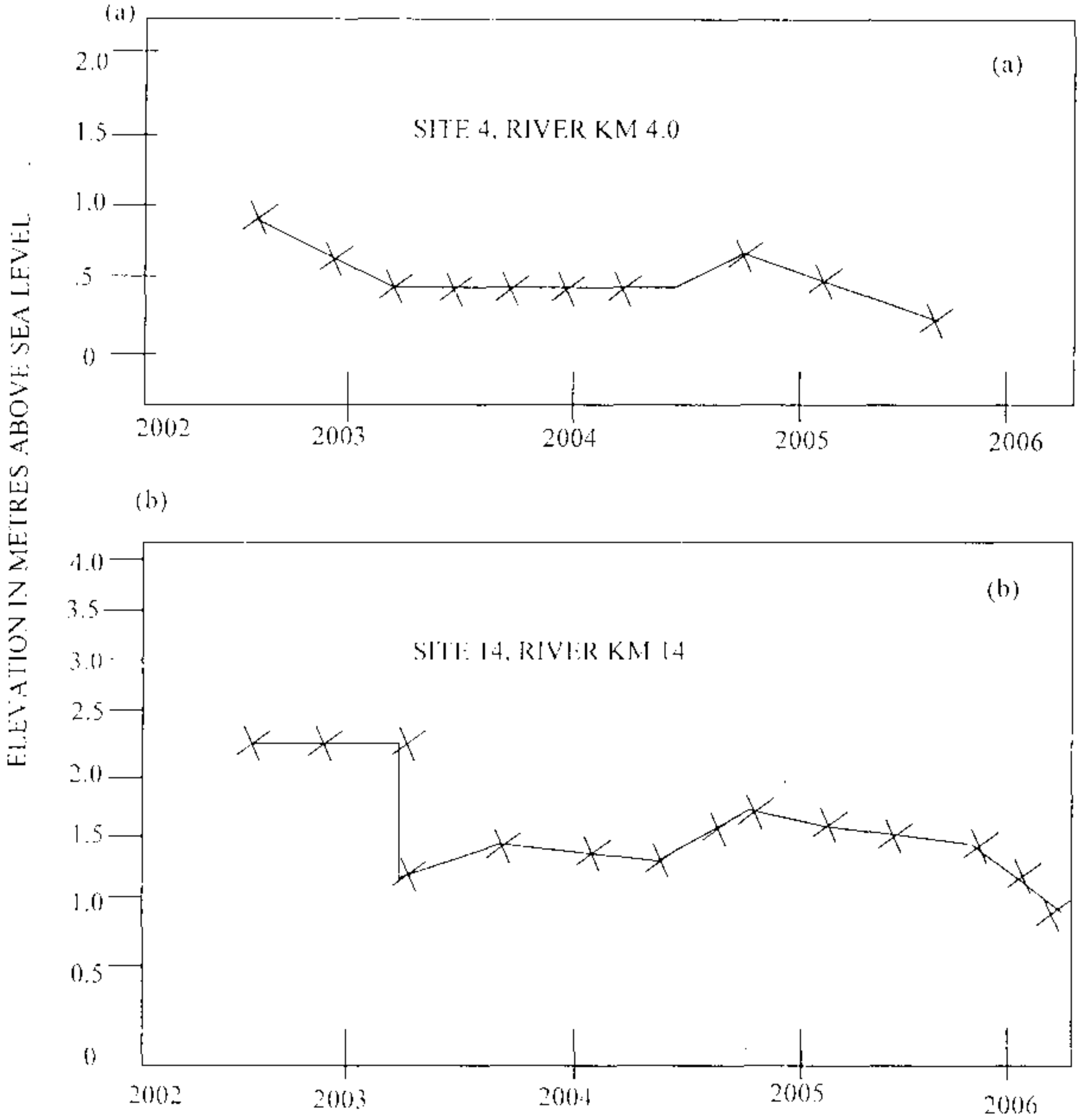


Fig. 1.6 (a,b) Trends of channel-bed elevation with time for two sites (4 and 14) on the river

Sand mining operation

Sand mining operations have had a major impact in the sand-bed reach. With increasingly dense settlement in the basin, and only restricted sources of sand for developments such as building, highway constructions, and other general purposes, there is a growing demand to remove sand. This will not necessarily lead to degradation of the channel. It is possible that the sand may be replaced by increasing quantities of sand in storage especially by erosion from the farmlands. Nonetheless, there is a concern that the continued removal of sand and other' coarse materials in excess of annual recruitment will result in long-term deterioration of fish habitat. Local problem like degradation may result w hich w ould lead to a changed pattern of erosion and deposition for many kilometres upstream or downstream. An acceptable resolution would be to remove limited quantities of sand from sites selected so that the river activity will develop in an acceptable way. But this would be substantially more expensive and difficult to administer than the proliferation of fixed, high-volume sites.

Navigation

At the moment there is limited commercial navigation in the studied reach. What can be seen are tow canoes guiding timber rafts downstream. To improve operations, dredging to cut passages through the major riffles. This would reduce local gradients and currents. If the passages were continually maintained, they would also increasingly constrain the river to a single, stabilized channel way, isolating many of the side channels. To some degree, the purported dredging in recent years that was aborted mid-way, because of lack of foresight and an explicit plan has only created deeper channel in some locations and deposition elsewhere. In the long term, this can only create pervasive morphological changes. This again will create a conflict between commercial development and the integrity of the river.

Conclusion

Aggradation, no doubt, increases the altitude of the channel-bed while degradation lowers it. In either case, and for any channel, there is bound to be some morphological changes because of the drastic changes in energy conditions that accompany any of the processes. These changes, as it were, will affect the river environment negatively in most cases. Careful attention is required to the development of river morphology restorations in order to appreciate the long-term impacts on the riverine habitat. Therefore, continuing attention to morphological development of the river is the key to successful long-term management.

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