IMPLICATIONS OF HYDRAULIC GEOMETRY EXPONENTS OF ZAMBIAN RIVERS

Sichingabula M. Henry
Department of Geography and Environmental Studies, School of Natural Sciences,
University of Zambia, P. O. Box 32379, Lusaka, Zambia

Corresponding email: Sichingabula@unza.zm; Sichingabula@yahoo.com

Abstract:

At-a-station and downstream hydraulic geometry exponents of rivers in Zambia, located in the central-southern African tropics, were analysed based on three power relations of width, depth and velocity plotted against discharge. Channel cross-sectional form and discharge data, for 55 gauging stations monitored by Department of Water Affairs between 1948 and 1984, the period with good data, were used. Of these stations, 12 were located in the Zambezi River sub-basin while 37 and 6 others were in the Kafue and Luangwa River basins, respectively. For downstream analysis, 14 stations located on the main channel of Kafue River were investigated. The objectives were to: (i) determine the hydraulic geometry relations of Zambian rivers for comparison with those of other regions of the world; (ii) assess the factors accounting for variations in the observed hydraulic geometry exponents; and (iii) draw some implications of Zambian rivers' hydraulic geometry exponents. Results of analysis showed that the obtained average at-a-station hydraulic geometry exponents for width (b), depth (f) and velocity (m) of Zambian rivers were 0.15, 0.38 and 0.47, respectively, and accorded well with similar results in the literature. Similarly, ranges of downstream exponents on the Kafue River of b = 0.50, f = 0.30 and m = 0.20 were also within the ranges of reported values. The plotting of most of at-a-station hydraulic geometry exponents on the right side of the tri-axial (ternary) diagram (f>b), implies that Zambian rivers are generally adapted to the transportation of fine-grained sediment ostensibly caused by the entrenchment of the river channels. The observation of m>f in some cases was interpreted as evidence that such streams possessed greater capacity of transporting large calibre bed load sediment. It is concluded that the behaviour of Zambian rivers is comparable to others in different physiographic regions of the world. However, unlike in temperate areas, the existence and influence of dambos in Zambia provides a complicating factor in the understanding of the behaviour of rivers.

Key words: *Hydraulic geometry exponents, at-a-station hydraulic geometry, downstream hydraulic geometry, tri-axial ternary diagram, streambed, sediment, dambo, river behaviour.*

INTRODUCTION

Rivers perform their primary functions of erosion, transport and deposition of sediment in a variety of ways. To efficiently achieve these functions, rivers adjust their channels by utilizing available degrees of freedom or variables which are related to channel form and hydrodynamics of flowing water. In a flowing river, channel variables interact in a complex fashion with one another such that there is yet no single mathematical model that can explain or predict such interactions. Hydraulic geometry which was introduced by Leopold and Maddock (1953) simplifies the analysis of the interaction between discharge and other variables and ushered in a new approach to the study of rivers. This paper is part of an on-going research on rivers in Zambia based in the Department of Geography and Environmental Studies at the University of Zambia, Lusaka. The purpose was to add more data and information on tropical rivers to that available in the literature, which is predominantly from humid temperate environments. The objectives of this study were to: (i) determine the hydraulic geometry relations of Zambian rivers for comparison with those in other regions of the world; (ii) assess the factors accounting for variations in observed hydraulic geometry exponents; and (iii) draw some implications of Zambian rivers' hydraulic geometry exponents.

This being the first study to investigate stream channel hydraulic dynamics in Zambia, it was considered necessary to begin by analyzing existing archival data before embarking on theoretical and/or field-based studies on stream hydraulics and other problems of sediment transport. Therefore, this study sought to make a contribution to the knowledge on hydraulic geometry relations in different physiographic and climatic regions of the world.

THEORETICAL BACKGROUND

Hydraulic geometry is a form of analysis introduced by Leopold and Maddock (1953) in which stream parameters of width (w), depth (d) and velocity (v), among other variables, were expressed as power functions of discharge (Q). The basic hydraulic geometry relations as power functions are of the form (Figure 1):

$$w = aQ^{b}, \qquad d = cQ^{f} \qquad \text{and} \qquad v = kQ^{m}$$

In order to satisfy the continuity equation ($Q = wdv$) the sum of the exponents ($b+f+m$) and the product of the constants (ack) should equal to unity. The interpretation of hydraulic geometry relations involves comparison and evaluation of exponents between gauging stations and between rivers located in different climatic and physiographic regions.

Since the classical work of Leopold and Maddock on hydraulic geometry relations many studies have so far been conducted in different climates and physiographical settings (e.g., Wolman, 1955; Langbein, 1964; Leopold, Wolman and Miller, 1964; Knighton, 1975; Park, 1977; Parker 1979; 1965; Ponton, 1972; Thornes, 1970; Richards, 1982; Allen, *et al.* 1994; Dudley, 2004; Stewardson, 2005; Riley, 1978). Most of the findings of these studies fit in the trends observed by Leopold and Maddock (1953). However, there are difficulties in hydraulic geometry studies which include, among others, the assumption that the relations are linear while some relationships are best described by non-linear equations (Richards, 1973; Phillips, 1990; Church, 1980); plus the complexity of channel adjustments attributable to the multivariate nature of natural systems (Maddock, 1969; Hey, 1978; Slingerland, 1981; Richards, 1976; 1982); extensive reviews of the hydraulic geometry (Singh, 2003) and theoretical approaches of understanding the relationships (Easton, 2010). Some studies have concentrated on 'extremal' hypotheses theoretical studies to identify system constraints or boundary conditions for estimating coefficient values in the power functions (Chang, 1980; Young and Song, 1979; Davis and Sutherland, 1983). To date theoretical studies have not provided unique quantitative solutions to the hydraulic geometry problems.

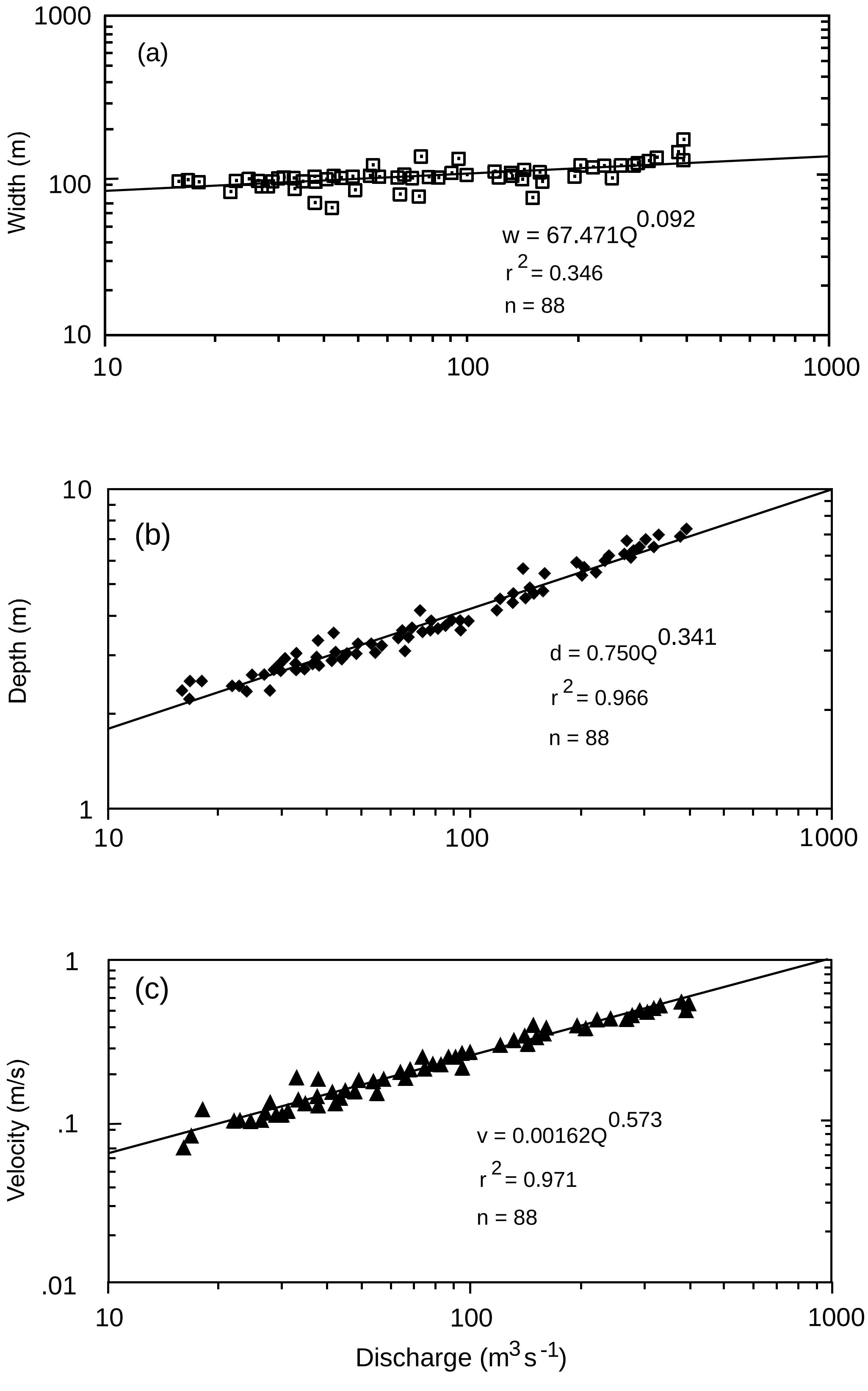


Figure 1: Examples of three at-a-station hydraulic geometry relations for Kafue River at Machiya Ferry Station (4-280), Zambia.

Fairly recently Hickin (1995), linked hydraulic geometry to in-channel processes and observed that the conventional power-function relations obscure some discontinuities in the fill and scour processes and discouraged their use to in-channel process studies.

The value of hydraulic geometry studies include, among others, the assessment of vertical and lateral channel changes, making inferences on effects about changes on channel form being able to discover causes of such changes (Thornes, 1977), and how it can be used in river engineering and other applications (Wharton, 1995). Thus, studies on channel changes in terms of hydraulic geometry are important in fluvial geomorphology because they enhance the understanding of river behaviour and the problem of sediment transport.

For comparative studies, the works by Park (1977) and Rhodes (1977) added a new dimension to hydraulic geometry studies by independently introducing the tri-axial diagram because it allowed for simultaneous assessment of variations in hydraulic variables as channels respond to changes in discharge at cross sections. Rhodes' (1977) subdivision of the ternary diagram on the basis of channel morphology and flow hydraulics allows, especially for deducing information on channel responses to increasing discharge. River characteristics of interest herein included amount and type of sediment carried, channel shape and changes in channel roughness. The tri-axial diagram was used in the interpretation of obtained hydraulic geometry exponents of Zambian rivers.

DESCRIPTION OF STUDY AREA

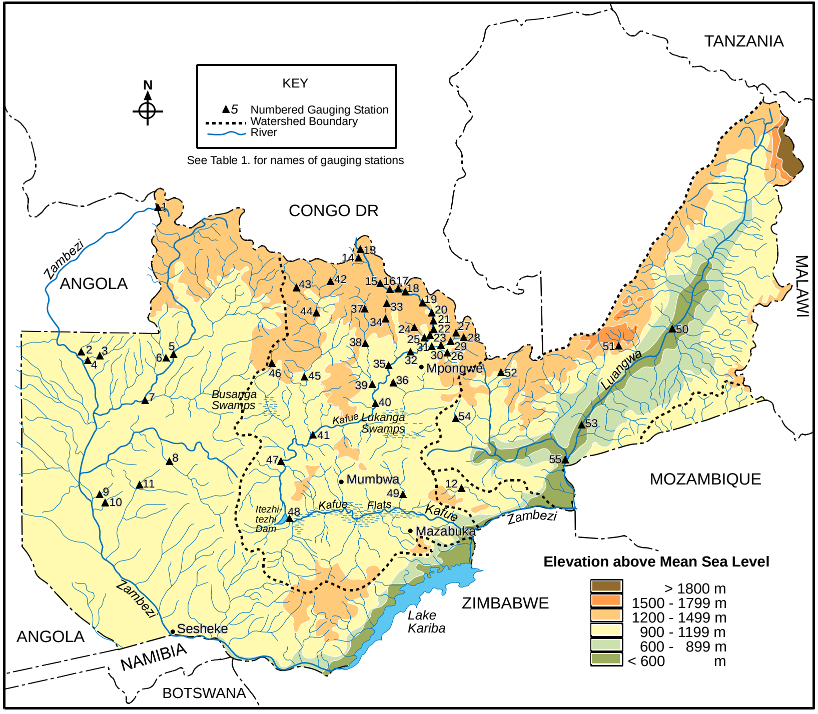
Zambia is located in the southern tropics of Africa and lies on the Central African plateau between latitudes 8° 14' and 18° 05' South and longitudes 22° 00' and 33° 45' East. Its climate is characterized by wet (November-April) and dry (May-October) seasons. Rainfall pattern, which is controlled by the southward and northward movements of the Inter-Tropical Convergence Zone (ITCZ), increases northwards. The physiographic features of the study area is characterized by valley floors lying above 300m above sea level along two major rivers, large flood plains, swampy areas, dambos, hills and plateaux (Dalal-Clayton et al. 1985; Mäckel, 1971; 1986). The area of interest is the Zambian portion of the Zambezi River system subdivided into three sub-basins, the Upper Zambezi, Kafue and Luangwa river basins (Figure 2a), briefly described below.

Zambezi River Basin

The Upper Zambezi River rises in North-Western Zambia, crosses into Angola and swings back into Zambia flowing in the southeasterly direction towards Victoria Falls and passes through Mozambique before entering the Indian Ocean (Figure 2a). Basement rocks in the Zambezi River basin are overlain by Kalahari Sands locally known as the Barotse Sands. These are deep poorly sorted and unconsolidated sand measuring up to 100 m in depth and covers most of the sub-basin (Drystal et al. 1972). Generally, Barotse Sands are mainly water-sorted sands with very little clay and silt content. These sands were deposited during the later Tertiary and Pleistocene periods during an arid phase. Alluvial flood plains of the Zambezi River basin are covered by thin layers of soil composed of peaty organic horizons, dark greyish brown to pale grey sands (Mäckel, 1971). On uplands are found soils rich in clay which promotes greater cohesion of stream banks (Balek and Perry 1973).

The Zambezi River basin has a well developed drainage network which is anomalously well entrenched for a region lacking relief and precipitation (Money, 1972: 105). Since surficial sediments in the Zambezi Kalahari system are composed predominantly of sand, the waters of the Zambezi and its tributaries are generally clear except at flood times when large quantities of sand are transported in suspension. Due to lack of data, no station on the main channel of Zambezi River was included in the analysis. Analyzed stations were those located to the east of the main Zambezi River channel upstream of Sesheke, on the Namibia-Zambian border. The annual unimodal hydrological regime for the Kabompo River at Watopa (1-650) in the Upper Zambezi basin, which peaks in April, is shown in Figure 2b together with the regimes for the Kafue River at Hook Bridge (4-669) and the Luangwa River at Mfuwe (5-650), which peak in March and February, respectively.

(a)



(b)

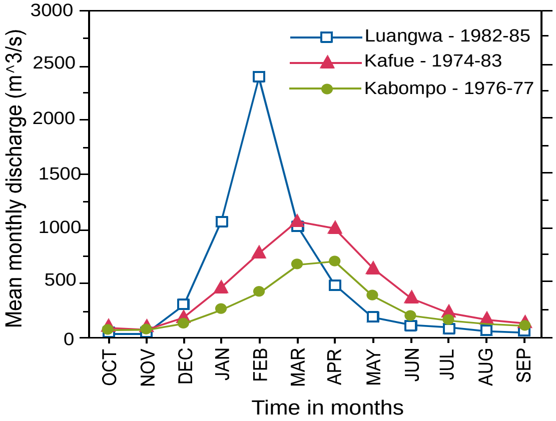


Figure 2: Map showing (a) physiographic features of the Zambezi River basin, and (b) hydrographs of selected three rivers in Zambia.

Kafue River Basin

Kafue River has its source near the Zambia-Congo DR border and initially flows southeastwards through the Copperbelt before adopting a southwesterly and southerly directions by the time it reaches Itezhi-Tezhi above the Kafue Flats before joining the Zambezi River downstream of Lake Kariba (Figure 2a). The geology of the Kafue River basin is generally composed of pre-Cambrian rocks with some granitic intrusions in places. In the headwaters region of Kafue River basin where the rainfall is high are found sandy to medium textured leached sandveldt soils (FAO, 1968). Moderately fine textured reddish soils are found in areas between Lukanga Swamps and Itezhi-Tezhi. Light soils are found on uplands especially in the western margins covered by Barotse Sands. The vegetation consists of woodlands in all sub-catchments with varying density of grasses on wetlands and dambos. Dominant woodland tree species are *Brachystegia* and *Combretum*. Riverine trees and some evergreen bush species occur in places along river banks (Sharma, 1984).

Luangwa River Basin

Luangwa River rises in the north-eastern part of Zambia near the Malawian border and flows in the south-westerly direction before turning south to join the Zambezi River at Luangwa on the Zambia-Zimbabwe-Mozambique border (Figure 2a). Most of the Luangwa River basin is underlain by pre-Cambrian crystalline igneous and metamorphic rocks and by Karoo sedimentary rocks. The Karoo rocks which comprise sandstones, mudstones and mals grit occupy the lower valleys and depressions. Luangwa River has a wide alluvial flood plain and a distinct meander belt ranging from 50 m to 200 m in width bordered by vertical banks of up to 5 m in height (Giardino, 1973). Luangwa River generally carries clay and silt sediment derived from local rocks. Soil types include yellowish-brown sandy soils with increasing clay content with depth; dark reddish brown clays and coarse alluvial sandy soils topped by dark loamy alluvium (Dodd and Patton, 1968; White 1973). These soils tend to produce cohesive river banks but easily collapse when undermined by flow currents. The vegetation types in the valley include grasslands in floodplains and dambos found almost everywhere, mopane woodland which occur mainly on vertisols and are dominated by *colophospermum mopane*, minor mixtures of *kirkia accuminata, sterculia africana* and other species such as the baobab. The Miombo woodland which covers mainly the plateau and escarpment country is characterized by *brachystegia jubelnardia* and *Isoberlinia* species.

DATA AND METHODS

Analysed data of channel form, discharge, width, depth of flow, stream velocity and dates of discharge measurement, were obtained from the Department of Water Affairs in Lusaka. Numbers of observations at each station varied and ranged from 11 to 198 with a majority of stations having more than 30 observations. Stations in remote parts of the Country had generally fewer observations than those in easily accessible areas. Although a large archival data set exists for over a century (1905-2007) most of it has not been analysed for understanding of various river plan forms and flow hydraulic characteristics. Good usable data was limited to the period 1948-1977 because after 1977 most river gauging stations were closed due to retrenchment of gauge readers.

Of the 55 study stations, 12 were located in the Zambezi River sub-basin, while 37 and 6 stations were in the Kafue and Luangwa River sub-basins (Figure 2a). Of the 37 stations in the Kafue River basin 14 were located on the main channel and were used in the downstream analysis of hydraulic geometry exponents. However, the total number of discharge measurements analysed in the downstream case on the Kafue River were thirty (30) because at some stations there were more than one event that had discharges equivalent to the mean annual flood ($Q_{2.33}$) to which the analyses were tied. The data analysed for the Kafue River was collected before 1974 when the construction of the Itezhi-Tezhi Dam, located immediately upstream of the Kafue Flats was completed (Figure 2a).

Lastly, selected bed and bank sediment samples collected in 2000 at four gauging stations were analysed to supplement flow cross section data. The analysis of bed and bank grain size data was done for the Kafue River at Hook Bridge station (4-669), Luangwa River at Mfuwe bridge station (5-650), Luangwa River at Great East Road (GER) Bridge station (5-940), and Chongwe River at Chongwe Bridge (5-025). The grain particle size distributions of samples were determined by sieving and weighing sub-samples of different fractions and results expressed as a percentage. Some of the grain size data for Luangwa River at Mfuwe bridge station were obtained from unpublished source (Karabassis, 1988). In order to assess causes of variations in the exponent values, the data were plotted on a tri-axial diagram which divides channels into 10 types based on geomorphic and hydraulic thresholds (Rhodes, 1977).

Accuracy of Data and Results

Undoubtedly, using data collected for different purposes for hydraulic analysis causes problems related to the accuracy and reliability of the data. For instance, it is likely that for some rivers the discharge was not always measured at same sites at different times due to changes in water levels and vegetation growth. Some data could also contain operator errors; but these were assumed to be small. For the resultant exponent values, no error analysis in the obtained exponent values was conducted albeit their existence in some appreciable amounts as Richards (1973) states, 'there is no *appriori* reason why linear power functions should best be described by hydraulic geometry relations'. The question of errors in exponent values has more to do with the merits of the hydraulic geometry approach rather than the inaccuracies of individual analyses. Thus, some errors inherent in obtained results may be simply the result of inappropriate application of the power analytical approach used, a problem which was outside the scope of this study.

ANALYSIS AND RESULTS

At-a-station Hydraulic Geometry

Analysis of 55 at-a-station hydraulic geometry data involved plotting and fitting multiplicative (logarithmic) regression lines to the relationships between discharge and three dependent variables of width, depth and velocity, and exponents of b, f and m compiled. During the analytical exercise, it was observed that for some stations, plots could be fitted by two different regression lines between different periods showing that channels had undergone some changes. Knighton (1975) referred to such changes as "phases" which he found to be related to changes caused by specific discharge events or to more gradual changes in channel morphology. Knighton's observations were confirmed in this study where changes in channel forms were observed to have occurred either after the passage of a flood event due to degradation as well as following a dry spell (drought) due to aggradation. For stations showing 'phase' changes in hydraulic relations, exponents for two different periods were reported separately. As a result, overall sets of exponents increased from 55 (i.e., number of gauging stations) to 61 analyses (Table 1).

Table 1 also shows that there were wide variations in at-a-station exponent values about the mean values of $b = 0.15$, $f = 0.38$ and $m = 0.47$. Of the 61 at-a-station sets of exponents, only 29 sets summed up to unity. These 29 sets included cases where the sum differed by ±5% from unity, the expected value (thus 0.95 to 1.05). For such cases the values of f and m exponents were adjusted to bring them to 1.00 by the method provided by Rhodes (1977). The ranges of exponents summing up to unity were found to be $0.01 \leq b \leq 0.47$, $0.17 \leq f \leq 0.70$ and $0.03 \leq m \leq 0.73$ with some minor variations between the three individual drainage basins studied. The b, f and m exponents of Zambian rivers varied widely in terms of frequency distribution within the zero to 1 range. All these values were found to be within those reported elsewhere in the world (Table 2A) In order to assess whether or not there were similarities in rivers' responses to changes in discharge, the 29 sets of exponents were plotted on a b-f-m tri-axial diagram using the plotting position suggested by Rhodes (1977; 1978). The remaining 32 sets that did not add up to unity were excluded from further analyses. The tri-axial diagram was divided into 10 channel types identified by Rhodes (1977: 76-83) by fitting lines representing geomorphic thresholds which greatly assisted in summarizing and interpretation of results. These channel types were based on constant values of width-depth ratio ($b = f$); competence ($m = f$), competence defined as the largest grain a stream can move as bed load (Morisawa, 1968: 48); Froude number ($m = f/2$), velocity-cross-sectional area ratio (related to the Darcy-Weisbach friction factor) ($m = b+f$); and slope-roughness ratio which is related to Manning equation ($m/f = 2/3$), among others. Out of ten, channel types 1, 5, 7 and 9 were not represented in the study possibly due to the small number (29) of at-a-station river stations analysed.

Table 1. Station data and at-a-station channel hydraulic geometry exponents for tropical rivers in Zambia.

	Station		Area	$Q \leq Q_{2.33}$	Sample	Channel Hydraulic Exponents*				Period of
No.	No.	River	(km^2)	(m^3 s^{-1})	size	b	f	m	Sum	measurement
ZAMBEZI RIVER SYSTEM										
1	1-080	Zambezi R. at Kaleni Hills	764	3	26	0.15	0.62	0.23	1.00	1977-77
2	1-130	Lunkunyi R. at Lunkunyi School	550	15	19	0.28	0.23	0.49	1.00	1971-77
3	1-145	Mokandu R. at Chivatu Village	3354	20	31	0.20	0.70	0.10	1.00	1970-77
4	1-138	Mokandu R. at Dipalata Mission	749	44	22	0.17	0.43	0.51	1.11	1971-77
5	1-610	Kabompo R. at Manyinga	64530	480	22	0.13	0.92	0.74	1.79	1971-77
6	1-630	Manyinga R. at Manyinga	1660	30	28	0.26	0.44	0.30	1.00	1971-77
7	1-650	Kabompo R, at Watopa	66450	550	48	0.04	0.40	0.70	1.14	1970-77
8	2-130	Luampa R. at Nyenga School	7020	20	69	0.27	0.47	0.26	1.00	1961-67; 70-76
9	2-340	Sefula R. at Sefula Bridge	140	2.5	31	0.14	0.53	0.33	1.00	1971-77
10	2-360	Kataba R. at Siandi Bridge	575	3	30	0.20	0.29	0.51	1.00	1971-77
11	2-475	Lui R, at Luatembo School	1854	30	30	0.42	0.37	0.29	1.08	1970-77
12	5-025	Chongwe R. at Chongwe Bridge	1813	40	118	0.02	0.18	0.80	1.00	1969-77
KAFUE RIVER SYSTEM										
13	4-005	Kafue R. at Kipushi	440	30	30	0.23	0.39	0.50	1.12	1970-74
		" "	440	30	30	0.25	0.32	0.43	1.00	1975-77
14	4-015	Muchindamu R. at Muchindamu	285	25		0.09	0.30	0.46	0.85	1963-77
15	4-040	Kafue R. at Ngosa Farm	4065	55	42	0.10	0.40	0.56	1.06	1963; 68-74
16	4-050	Kafue R. at Raglan Farm	4999	75	25	0.05	0.56	0.51	1.12	1973-77
17	4-060	Kafue R. at Chililabombwe	5206	105	65	0.14	0.47	0.63	1.24	1958; 60-62; 71-74
18	4-090	Kafue R. at Kafironda	7148	220	51	0.49	0.61	0.28	1.38	1971-77
19	4-120	Mwambashi R. at Mwambashi	4999		94	0.41	0.47	0.38	1.26	1959-60; 71-77
20	4-130	Kafue R. at Smith's Bridge	8599	200	31	0.45	0.59	0.49	1.43	1959-63
		" "	8599	200	72	0.47	0.49	0.04	1.00	1971-76
21	4-150	Kafue R. at Wusakile Bridge	9195	260	23	0.25	0.50	0.39	1.14	1971-77
22	4-152	Kamfinsa R. at Kamfisa	191	18	22	0.07	0.37	0.56	1.00	1971-77
23	4-170	Baluba R. at Baluba	339	2.5	35	0.11	0.17	0.72	1.00	1970-77
24	4-180	Chapula R. / St. Joseph's Mission	18	2	60	0.20	0.26	0.54	1.00	1970-77
25	4-200	Kafue R. at Mpatamato	11655	340	198	0.09	0.61	0.45	1.15	1952-56; 59-67; 71-77
26	4-205	Kafulafuta R. at Ibenga Mission	2499	26	23	0.13	0.17	0.70	1.00	1971-77
		" "	2499	26	19	0.39	0.41	0.13	0.93	1974-77
27	4-210	Kafubu R. at Itawa Dambo	306	16	43	0.10	0.24	0.66	1.00	1971-77
28	4-239	Munkulungwe R. at Kaposa	210	7	53	0.12	0.27	0.43	0.82	1971-77

Table 1 concluded.

No.	Station No.	River	Area (km^2)	$Q \leq Q_{2.33}$ ($m^3 s^{-1}$)	Sample size	Channel Hydraulic Exponents* b	f	m	Sum	Period of measurement
29	4-240	Kafubu R. at Fisenge Culverts	951	18	58	0.20	0.34	0.23	0.77	1971-77
30	4-245	Kafubu R. at Masaiti Bridge	1375	33	35	0.32	0.25	0.22	0.79	1969-73; 75-77
31	4-250	Kafulafuta R. at Miputu Hills	4817	70	36	0.08	0.51	0.54	1.13	1969-77
32	4-260	Kafue R. at Ndubeni	18726	410	73	0.09	0.59	0.67	1.35	1971-77
33	4-266	Mpopo R. at Mpopo School	69	2	42	0.09	0.49	0.09	0.67	1971-77
34	4-267	Lufwanyama R. at Mpopo School	984	25	52	0.28	0.69	0.03	1.00	1969-77
35	4-280	Kafue R. at Machiya Ferry	22922	460	88	0.09	0.34	0.57	1.00	1971-77
36	4-281	Ipumbu R. at Machiya	598	10	21	0.27	0.34	0.39	1.00	1971-77
37	4-302	Luswishi R. at Lwendo	2668	90	37	0.10	0.22	0.38	0.70	1969-77
38	4-310	Luswishi R. at Kilundu	3600	95	46	0.12	0.70	0.31	1.13	1971-77
39	4-340	Luswishi R. at Kangondi	8708	110	34	0.10	0.44	0.46	1.00	1971-77
40	4-350	Kafue R. at Chilenga	34162	580	37	0.06	0.55	0.52	1.13	1970-73; 75-77
41	4-450	Kafue R. at Lubungu	54442	560	46	0.06	0.36	0.58	1.00	1967-68; 70-77
42	4-460	Lunga R. at Konikombe Hills	619	16	39	0.28	0.35	0.37	1.00	1970-77
43	4-500	Mutanda R. at Mutanda Mission	1705	60	28	0.12	0.20	0.41	0.73	1969-72; 74-77
		" "	1705	60	11	0.02	0.25	0.73	1.00	1975-77
44	4-510	Lunga R. at Mujimanzovu	7977	125	24	0.15	1.00	0.98	2.14	1969-72; 74-77
		" "	7977	125	18	0.15	0.44	0.41	1.00	1974-77
45	4-550	Lunga R. at Kelongwa School	19555	310	64	0.04	0.33	0.63	1.00	1969-73; 76-77
46	4-620	Lufupa R.near Kabompo Pump Hse	20	18	118	0.14	0.12	0.54	0.90	1964-65; 68-77
47	4-669	Kafue R. at Hook Bridge	95053	1100	43	0.01	0.28	0.85	1.14	1973-78
48	4-710	Kafue R. at Itezhi-Tezhi	105620	1200	149	0.12	0.36	0.52	1.00	1973-77
49	4-940	Mwembeshi R. near Shibuyunji	3885	13	21	0.30	0.53	0.17	1.00	1963-64; 71-72; 76
LUANGWA RIVER SYSTEM										
50	5-650	Luangwa R. at Mfuwe	4630	530	130	0.01	0.41	0.58	1.00	1978-84
51	5-670	Lusiwasi R. at Masase	995	24	197	0.08	0.35	0.57	1.00	1968-77
52	5-755	Chiwefwe R. at near Mkushi	180	4	37	0.22	0.56	0.22	1.00	1963-64; 70-71; 73-77
53	5-800	Luangwa R. at Lwembe	113590	700	63	0.21	0.28	0.19	0.68	1976-77?
54	5-815	Mulungushi R. at G.N.R. Bridge	1448	60	87	0.15	0.30	0.62	1.07	1967-74
		" "	1448	60	30	0.15	0.30	0.62	1.09	1975-77
55	5-940	Luangwa R. at Luangwa Bridge	143820	900	55	0.12	0.37	0.31	0.80	1948-51; 55-60; 63-64

* Exponents of f and m adjusted proportionately for the sum to equal unity by the method devised by Rhodes (1974) in 5 cases where sums ranged from 0.95 to 1.05 inclusive.

Table 2. Comparison of distribution data of hydraulic geometry exponents of rivers around the world.

TYPE OF ANALYSIS	**Source of Data**	**Hydraulic Geometry Exponents**			
		n	**b**	**f**	**m**
A. AT-A-STATION					
Range	**Kafue River – this study**	**61**	**0.01-0.49**	**0.12-1.00**	**0.03-0.98**
	Rhodes (1974: 194)	587	0.00-0.84	0.01-0.84	0.03-0.99
Modal Class	**Kafue River – this study**	61	0.10-0.20	0.30-0.40	0.50-0.60
	Rhodes (1977: 93)	587	0.00-0.10	0.40-0.50	0.40-0.50
Mean	**Kafue River – this study**	**61**	**0.15**	**0.38**	**0.47**
	Wolman (1955)		0.04	0.41	0.55
	Langbein and Leopold (1962)		0.23	0.42	0.35
	Leopold et al. (1964)	158	0.12	0.45	0.43
	Coates (1969)	18	0.36	0.20	0.44
	Wilcox (1971)		0.09	0.36	0.53
	Ponton (1972)		0.21	0.32	0.50
	Church (1980)		0.22	0.31	0.48
	Abrahams (1984)	8	0.419	-0.064	0.632
	Rhoads (1991)	252	0.50	0.34	-
B. DOWNSTREAM					
Mean	**Kafue River – this study**	**30**	**0.50**	**0.30**	**0.20**
	Langbein and Leopold (1962)		0.60	0.30	0.10
	Thornes (1970)		0.40	0.34	0.25
	Smith (1974)		0.55	0.36	0.09
	Poton 1972)		0.80	0.44	-0.23
	Parker (1979)		0.50	0.415	0.085
	Allen et al. (1994)	674	0.557	0.341	0.104

Although two of the study basins had very few stations, average exponent values in the Kafue, Zambezi and Luangwa River sub-basins were found to be: (b = 0.20, f = 0.33, m = 0.47), (b = 0.14, f = 0.37, m = 0.49) and (b = 0.10, f = 0.44, m = 0.46), respectively. The overall mean exponents were found to be: b = 0.15, f = 0.38 and m = 0.47 and plotted on the right side of the ternary diagram as did all other points with the exception of one (Figure 3a). Overall, streams that plot together in a particular area of the ternary diagram tend to experience similar directions of change to increasing discharge even though the exact rates may differ considerably.

Downstream Hydraulic Geometry

Downstream analysis of hydraulic exponents was based on 14 stations located on the main channel of the Kafue River. The analysed width, depth and velocity measurements were for uniform discharge of approximately mean annual flood ($Q_{2.33}$) determined by flood frequency analysis of the annual series (Darlymple, 1960). Obtained average downstream exponents for the Kafue River were b = 0.50, f = 0.30 and m = 0.20. These together with others in the literature plus some theoretical values for comparison purposes, are shown in

Table 2B. Figure 3b shows that on the Kafue River the exponents for width, depth and velocity all increased with discharge in the downstream direction.

Stream-bed and Bank Composition

Stream-bed and bank material composition is important for understanding stream adjustments. As such, limited bed and bank field grain-size data was used to explain the behaviour of some rivers at selected studied stations. For instance, the Kafue River at Hook Bridge station (4-669) was found to be composed of more coarse bank materials (D_{90} = 3.5 mm) than bed materials with fine sand predominating (D_{90} = 0.13 mm) (Figure 4a). At Chongwe River Bridge station (5-025) (not plotted), it was found that stream banks were composed largely of coarse silt (D_{90} = 0.05 mm) while the bed was predominantly fine sand (D_{90} = 0.15 mm).

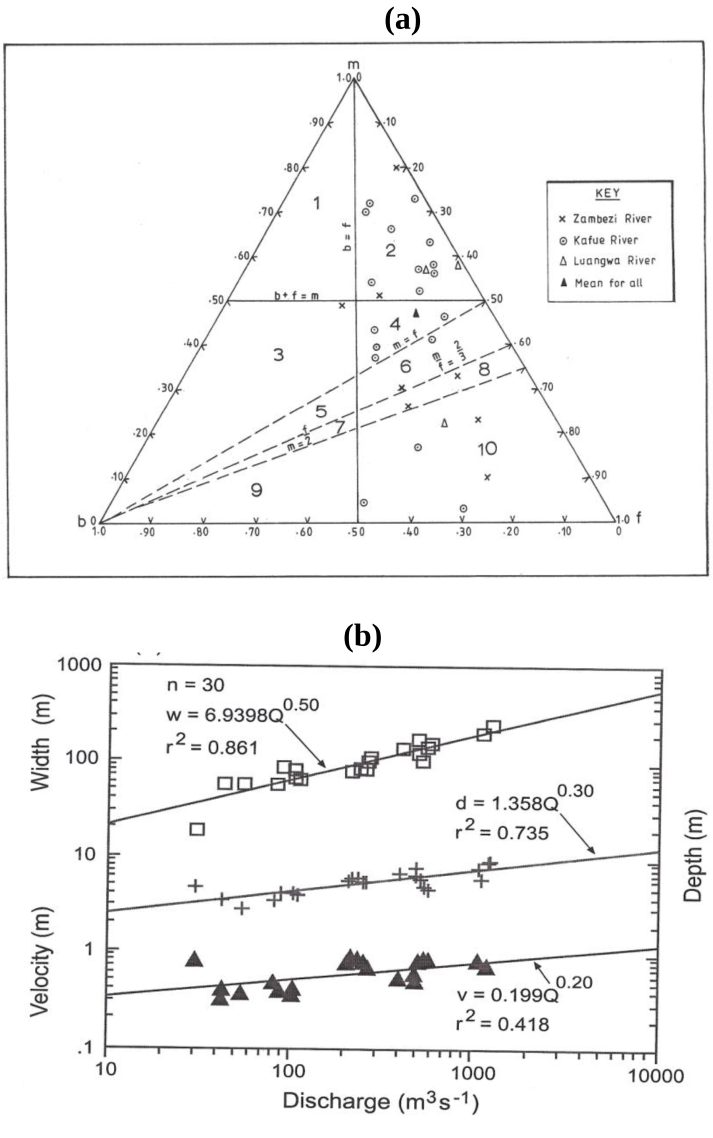


Figure 3: Plots of (a) tri-axial diagram of at-a-station hydraulic geometry of Zambian rivers; and (b) downstream hydraulic relations of Kafue River, Zambia.

For the two stations on Luangwa River, Mfuwe bridge (5-650) and at GER bridge (5-940), bed materials were found to be predominantly coarse sand (D_{90} = 0.50 mm) and fine sand (D_{90} = 0.18 mm), respectively. In contrast, bed bank materials were composed of fine-grained sediment (D_{90} = 0.08) at Mfuwe station while the channel bed at Luangwa GER were mainly composed of medium grained-sized sediment (D_{90} = 0.25 mm) (Figure 4a).

Overall, Figure 4a shows a larger difference in grain sizes between bed and bank sediment at Hook Bridge station (4-669) based on the observed D_{90} values. In contrast, on Luangwa River at Mfuwe station (5-650) the difference in grain sizes between bed and bank materials is small. But it is probably the case that the range between bed and bank materials, in some cases increases in the downstream direction as the only grain size curve for the Luangwa River Great East Road station (5-940) shows.

DISCUSSION

The tri-axial diagram developed by Rhodes (1977) and Park (1977), was useful in summarizing hydraulic geometry exponents. The division of the graph into different channel types also greatly facilitated the interpretation of results. The interpretation of results was based on existing basin and site information obtained from field and documentary sources because controlling factors of hydraulic geometry exponents relate to channel morphology and hydrodynamics of river flow.

Because climatic controls on rates of change in width, depth and velocity with changes in discharge at-a-station and in the downstream direction are at best speculative; exponent values have only been partially linked to climatic controls. Thus, for the tropics the influence of dambos which are largely the consequence of dry and wet and seasonal climate, is the one factor that partly attributed to observed variations in exponent values of rivers in Zambia to those for other world rivers. Rhodes' (1977; 1978) ten divisions of the ternary diagram formed the basis upon which the observed exponent results were interpreted. However, the discussion of at-a-station and downstream results of hydraulic geometry exponents below mainly focuses on three sub-divisions of the diagram, namely, $b = f$, $m = f$ and $m = b+m$ lines which represented the majority of the plotted data.

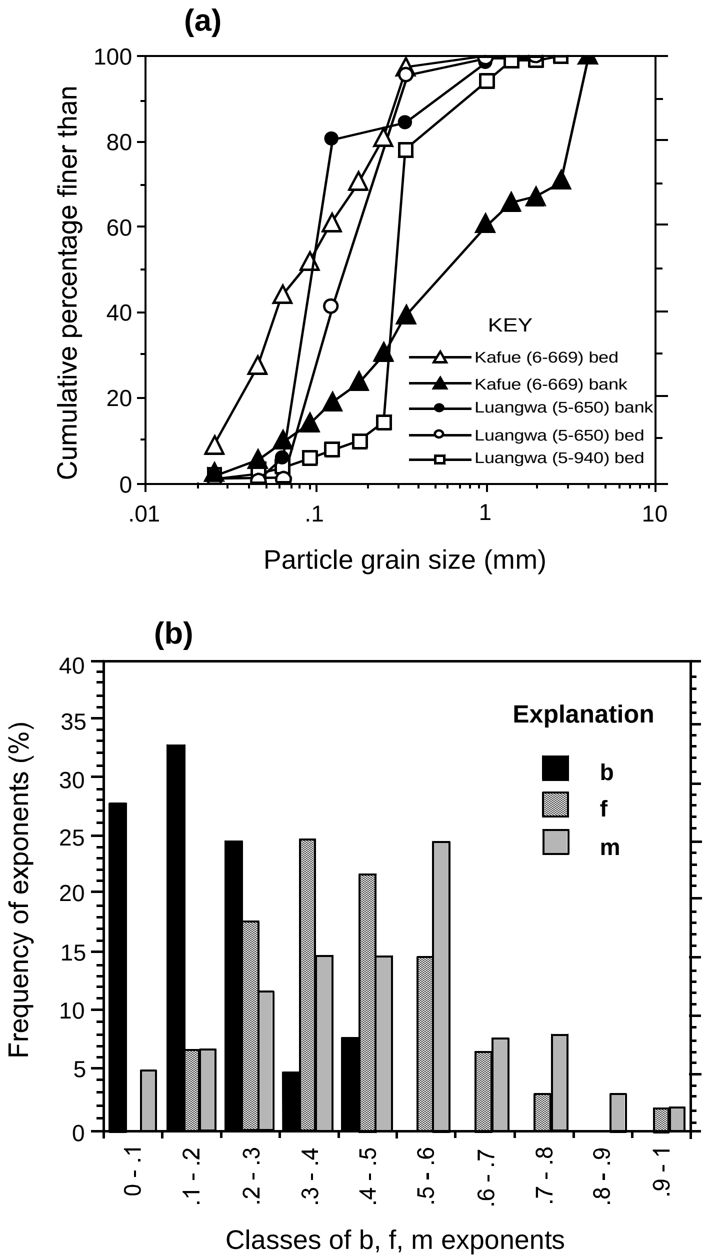


Figure 4: Plot of (a) particle size distribution of stream bed and bank materials at selected gauging stations, and (b) frequency distribution of at-a-station b, f, m hydraulic geometry exponents of rivers in Zambia

At-a-station Hydraulic Geometry

The b = f line

With the exception of one, all stations plot on the right side of the b = f line on the tri-axial diagram (Figure 3a) showing that the exponent for depth (f) was greater than that for width (b). This situation implies a close relationship between rates of change in depth and width and bed and bank materials and type of sediment rivers transport. Since channel shape and relative stability of bed and bank materials have been shown to be interrelated (Schumm, 1960), the general observation in this study that f > b indicates that channel beds respond at faster rates than does width to changes in discharge. This implies that most stream beds in Zambia were more easily eroded than stream banks (Rhodes, 1977: 76).

Part of the explanation for this could be related to the influence of dambos which occur in a variety of landforms (headwaters regions - headwater dambos; scarp zones - scarp or hanging dambos; river margins - river dambos), vegetation types (mainly miombo woodlands), and under different geological conditions (granitic to Kalahari sands) (Acres *et al.* 1985; Whitlow, 1984; 1985). By their nature, dambos tend to promote the accumulation of clays and silts in marshy areas and stream banks. It is believed that the processes of *dambo* development and subsequent degradation influence, over time, channel hydraulic geometry and behaviour of rivers. But more research is required to find out more on how dambos influence the character of rivers in tropical regions.

Rhodes' (1977) observation of $b < f$ for 90% of the sites is partly confirmed by this study where 54 (89%) of the stations were in the $b < f$ zone of the ternary diagram. Of these stations, 10 (19%) and 16 (30%) had sums of exponents less than and greater than unity, respectively (Figure 4b). This is not unexpected for Zambian rivers which are located in the tropics where depths of weathering are great, and where rivers generally flow on deep unconsolidated regolith. This reasoning and the limited information on site characteristics of rivers are based on the author's observations and experience obtained from the time he worked as Hydrologist, Department of Water Affairs, Lusaka, in the early 1980s and his continued research work on Zambian rivers in later years (Sichingabula, 1996; 1999a; 1999b; 1999c: Gilvear *et al.* 2000; Sichingabula *et al.* 2007).

For the observation of $b < f$ to be properly interpreted requires analysis of stream bank and bed composition materials. In Figure 4a, some sediment samples collected in year 2000 on three studied rivers revealed that grain particle size of bank materials were generally in the silt to fine sand range, while those of bed materials ranged from fine to coarse sand. Thus, based on clay content, it can be said that stream banks composed more of finer sediment were less susceptible to erosion than stream-beds which were composed largely of coarse materials.

Undoubtedly, bank materials are not the only factor influencing variation of channels as discharge changes. Huang and Nanson (1995; 2000) statistically found that bank strength has a significant influence on channel width but an insignificant influence on channel depth and cross-sectional area. Thus, bank sediment composition is the most important variable reflecting bank-erosion-resistance status. This is because basal sediment is subjected directly by fluvial entrainment whereas cohesive upper bank sediment erodes largely by the collapse of cantilevered overhangs (Thorne, 1979). Riverine vegetation found along most perennial streams present the other complicating factor to channel processes by retarding bank erosion except in situations where top bank sediment are underlain by sandy units which leads to undermining by caving and eventual collapse aided by the weight of trees on bank lines (Gilvear *et al.* 2000).

The other complicating factor is that the b-to-f ratios indicate changes in the width-depth relationships and not the absolute values of the variables. Rhodes (1977) points out that a cross section may have a relatively large w/d ratio for various discharges even though f is greater than b because the b/f ratio is just an indication of the change in the shape of the water cross section with respect to changes in discharge.

Similarly, with respect to the relationship between the rate of change in the b/f ratio and sediment transport, Rhodes (1977: 79) says that those channels that plot on the right side of the tri-axial diagram may have shapes that are best adapted to transporting fine-grained sediments, especially the deep and narrow channels. In contrast, wide and shallow channels are generally adapted to transporting large amounts of bed load (Morisawa, 1968; Leopold and Maddock, 1953). Based on this theoretical information, Zambian rivers could be said to transport mainly fine-grained sediment as evidenced by the plotting on the right side of the tri-axial diagram of most stations (Figure 4a). Part of the reason for this is that most rivers are entrenched. Among the rivers which transport coarse sediment load is the Kafue River, immediately upstream of Itezhi-Tezhi Dam where in some reaches it flows on granitic bedrock.

The m = f Line

The characterization that Zambian rivers carry mostly fine-grained sediment in Figure 3a is further supported by the plotting of a majority of points (19 out of 29) above the m = f line. Rivers which plot above this line increase their competence with increasing discharge while those that plot below it do not. Wilcock (1971) in an empirical study of shear stress and competence concluded that stream competence tends to increase only when the rate of increase in velocity (m) equals or exceeds the rate of increase in depth (f). This conclusion is partly confirmed by this study which found that in a majority of cases m was greater than f. This observation is further supported by Leopold and Maddock (1953: 28) who stated that an increase in suspended sediment transport requires an increase in velocity and a reduction in depth. But these changes are complicated by simultaneous interactions with other variables.

However, at a basin level considering only the Kafue and Zambezi rivers, 5 out of 8 cases plot below the m = f line in the Zambezi River basin which confirms that it is mainly designed to transporting fine-grained sediment. In the Kafue River basin, 14 out of 18 cases plot above the m = f line which implies that in this basin, rivers have greater potential for transportation of large-grained sediment than streams in the Zambezi River basin. This observation is further supported by another observation that 10 out 18 stations in the Kafue River basin plot below the m = b+f line (Figure 4a), characteristic of channels that experience very rapid increases in velocity with discharge (Rhodes, 1977: 80) at the expense of cross-sectional area.

The m = b+m line

The situation which is obtained when m > b+f is related to channel stability and a reduction in flow resistance. When velocity increases faster than channel area (m > b+f), as it generally does in the Kafue River basin, this implies that the channel is quite stable and little erosion of the bed and banks takes place. Therefore, in the Kafue River it is probable that stability of its channel is achieved more by erosion of the bed than banks which likely increases suspended sediment transport thereby effecting a reduction in flow resistance. The implication of a decrease in flow resistance when velocity increases faster than cross-sectional area is supported, among other studies, by Richards (1973: 887) who stated that a very rapid increase in velocity with increasing discharge (m > 0.50) is associated with a rapid decrease in the Darcy-Weisbach friction factor.

The small size of the sample analysed in this study precluded the discussion of other divisions of the tri-axial diagram. Instead a brief discussion of channel types fitting Rhodes' (1977) classification is presented (Table 3).

Table 3: Frequency distribution of channel types based on stream competence in Zambia.

Channel Type	Frequency of channel types	
	No.	(%)
1 (most probable)	0	0
2	14	48
3	1	3
4	4	14
5	0	0
6	2	7
7	0	0
8	2	7
9	0	0
10 (least probable)	6	21
Total	**29**	**100**

According to Rhodes (1977: 82) channels designated as type 1 should have the greatest competence for transporting sediment and those assigned to type 10 should be the least competent. Overall, Table 3 shows that four channel types, namely, 1, 5, 7, and 9 were not represented among studied rivers in Zambia. Channel type 6 which Langbein and Leopold (1974) proposed to be the most probable channel form (with exponents of b = 0.23, f = 0.42 and m = 0.35) in this study, this channel type occurred in only 7% of the cases. Channel type 2 was found to be the most common occurring in 48% (Figure 4b) of the cases and this accorded well with Rhodes' (1977) observation.

By comparing modal class frequencies of the three exponents obtained in this study (b, f, and m) with data in the literature analysed and presented by Rhodes (1977: 93) (Table 3), it is evident that hydraulic geometry responses of Zambian tropical rivers do not differ much from responses of rivers in temperate humid regions. However, at-a-station the range, modal class and mean values of b for Zambian rivers were generally found to be lower than those of other world rivers, while range and mean values of f and m for Zambian rivers were found to be slightly higher than other rivers. Additionally, Figure 4b also shows that the distribution of b values is negatively skewed to the left with the mean being slightly greater than the median. By contrast, the frequency of f and m values almost fit the normal distribution except that the f mean is greater than the median while the mean for m is less than the median value.

The substantial variations in the b/f and m/f ratios observed can be accounted for by various cross-sectional shapes, planform types, and sequences of pool and riffles found in river reaches (Ferguson, 1986). In this study, due to lack of detailed information on site characteristics at study stations, individual values of the exponents could not be tied to cross-sectional shapes and planform types most represented by the sample size.

The influence of dambos on character of channels merits detailed investigation because dambos exert considerable control on runoff generation and sediment supply to channels in terms of magnitude and timing during and after rainfall events.

Downstream Hydraulic Geometry

The one point average downstream hydraulic geometry exponents obtained for the Kafue River has not been plotted on the tri-axial diagram. Therefore, the interpretation of results in Table 2B was based on relationships between different combinations of exponents of b, f and m. Variations in such relationships reflect not only the morphological character of river channels but also the amount of sediment the Kafue River transports and the nature of its bed and bank materials.

Downstream changes in hydraulic changes are important in view of developments taking place within the Kafue River basin. Hydraulic geometry, if considered as a practical analytical tool, could be used to predict likely environmental outcomes of major developmental projects in the Kafue River basin because man's intervention into fluvial systems does not always produce desirable results. The Kafue River basin has been the focus of large scale development projects such as dam construction for hydro-electric power generation (at Itezhi-Tezhi and Kafue Gorge) and irrigation schemes (e.g., Nakambala in Mazabuka District and Kafue Sugar Estates located on northern banks of the Kafue Flats west of Lusaka). The impact of these large scale projects on rivers processes is not well understood today.

In terms of hydraulic geometry, factors from which information about channel changes the Kafue River may undergo that can be discerned include: the b = f (b/f) ratio and channel shape and m = f (velocity-depth ratio and channel competence) (Rhodes, 1987), among others. These factors are discussed below in relation to changes of downstream hydraulic geometry exponents.

The b/f Ratio

When b is greater than f a river is characterized by relatively wider and shallower channel in the downstream direction and is adapted to the transportation of large calibre bed load. This is the case on the Kafue River where b and f values were found to be 0.50 and 0.30, respectively (Figure 3b). This observation is supported in part by the character of the bed of the Kafue River immediately upstream and downstream of Kafue Hook Bridge station (4-669), which is armoured with coarse-grained sediment particles. This is because in this reach Kafue River flows on granitic bedrock exposed by the down cutting of the valley. Unfortunately, there is no archival data to indicate how much bed load the Kafue transports in this reach.

Similarly, the relatively high downstream b/f ratio (1.667) found on Kafue River which implies that this river mainly transports low suspended sediment load, there are not sufficient data to confirm this. However, the limited unpublished sediment data obtained from Water Affairs does show that sediment concentrations in the Kafue River basin are low (ranging from 3 to 437 mg L^{-1} per day) with a daily mean of 196 mg L^{-1} in 1974 and 1975 water years (Sichingabula, 1996). With a mean annual discharge of 336 m^3 s^{-1}, the mean annual suspended sediment transported by the Kafue River was found to be about 5,690 tonnes per year. This is a low value compared to sediment loads transported by many world rivers such as the Fraser River in Canada (e.g., Sichingabula, 1994; 1999b). More sediment data are required to confirm the above assertion that Kafue River transports a low annual suspended sediment load.

Since low b/f ratios are associated with large sediment loads (Leopold and Maddock, 1953) high b/f ratio (1.667) and the implied transportation of low sediment by the Kafue River suggest considerable cohesion in materials forming channel boundary probably due to high clay content. Currently no detailed archival data exists on characteristics of materials forming channel boundary along the Kafue River to confirm the above statement. Elsewhere, Osterkamp *et al*. (1983) observed that large w/d ratios and high b/f values are produced when the cohesiveness of the material increase very little downstream. But the Kafue basin is largely characterized by subdued topography due to the existence of dambos in headwaters regions, and along river margins (Acres *et al.* 1985; Mäckel, 1985). Undoubtedly, dambos influence the amount of sediment entering the channel from slopes due the existence of dense grassy vegetation cover in central parts of dambos.

The m/f Ratio

The ratio of the rate of change of velocity (m) to rate of change of depth (f) is related to shear stress via flow roughness. On Kafue River where $m = 0.20$ and $f = 0.30$, thus ($m < f$), it is probable that the river experiences little downstream increase in competence for sediment transport. This is because velocity increases in the downstream direction (Figure 3b) and shear may also decrease downstream even though velocity increases (Rhodes, 1987: 150). Since competence increases only when velocity increase faster than depth (Wilcock, 1971), the m/f ratio gives clues of the amount of sediment rivers carry.

Langbein (1965) observed that m/f values less than 1 are associated with rivers where suspended sediment concentration decreases in the downstream direction. On Kafue River where a low m/f ratio was found to be 0.667, this implies that this river carries low suspended sediment load in the downstream direction. This is partly accounted for by the existence of Kafue Flats in the middle reaches of the Kafue River. It has already been indicated that Kafue River generally transports a low annual suspended sediment load. However, more data at a number of stations along the main channel are required than is currently available to assess the nature of sediment movement in the downstream direction. Scanty data on suspended sediment concentrations were only available at two sites, Kafue Hook Bridge (4-669) and Itezhi-Tezhi (4-710) stations.

Overall, better understanding of variations in hydraulic geometry variables in relation to downstream sediment transport and how channel form changes requires more data on sediment transport and bank material composition. The existence of dambos in Zambia undoubtedly influences channel hydraulic geometry and presents one complicating factor in the comparison of the behaviour of rivers located in the tropics to those in temperate areas.

Conclusion

Average at-a-station hydraulic geometry exponents of Zambian rivers were found to be $b = 0.15$, $f = 0.38$ and $m = 0.47$ with about half of the sets of exponents summing up to unity. Relations of at-a-station variation between b and f, m and f, and m and b+f ratios, all related to channel cross-section shape; competence and friction seem to indicate that Zambian rivers are adapted to the transportation of fine-grained sediment. This is because a majority of river reaches in Zambia cannot be classified as gravel-bed. Also, the high b/f and low m/f ratios found in the downstream direction on Kafue River imply that this river transports low suspended sediment loads, though more sediment data is required than is available to confirm this assertion. Despite these findings, some exponent values of Zambian rivers were, undoubtedly, the consequence of un-researched influence of dambos on river hydraulics and sediment transport. Thus, unlike in temperate areas, the existence and influence of dambos in Zambia provides a complicating factor in the understanding of the behaviour of rivers. The study of dambos on these aspects should be the pre-occupation of future research on river studies in Zambia.

Acknowledgements

The financial assistance provided by the University of Zambia for this study is gratefully acknowledged. I am grateful to Mr. Joseph Chalila for drawing of maps and graphs, Mr. Evaristo Kapungwe for assistance in collection of data, the Department of Water Affairs and staff in the Hydrological Section for the supply of archival river cross-sectional data.

REFERENCES

Abrahams, A. D., 1984. ‘Channel networks: A geomorphological perspective.’ *Water Resources Research*, 20, 161-188.

Acres, D. B, Blair, A., King, R. B., Lawton, R. M, Mitchell, A. J. B. and Rackham, L. J., 1985. ‘African dambos: their distribution, characteristics and use.’ *Zeitschrift fur Geomorphologie New Folge Supplement band*, 52, 63-86.

Allen, P. M., Arnold, J. G. and Byars, B. W., 1994. ‘Downstream channel geometry for use of in planning-level models.’ *Water Resources Bulletin*, 30, 4, 663-671.

Balek, J. and Perry, J. E., 1973. Hydrology of seasonally inundated African headwater swamps. *Journal of Hydrology*, 19, 227-249.

Carlston, C. W., 1969. ‘Downstream variations in the hydraulic geometry of streams: special emphasis on mean velocity.’ American Journal of Science, 267, 499-509.

Chang, H. H., 1980. ‘Geometry of gravel streams’. *Journal of Hydraulic Division America Society of Civil Engineers* 106, HY9, 1443-1456.

Church, M., 1980. On the equation of hydraulic geometry. Department of Geography, University of British Columbia, Vancouver, Canada.

Coates, D. R., 1969. ‘Hydraulic geometry in a glaciated region.’ *Transactions, American Geophysical Union*, 50, 149.

Dalal-Clayton, D. B., English, E., Williams, G.J., and Spaargaren, O. 1985. A geomorphic legend for Zambia. Soil Survey Unit, Research Branch, Department of Agriculture, Lusaka, 65 p.

Darlymple, T., 1960. ‘Flood frequency analysis.’ *US Geological Survey, Water Supply Paper*, 1543-A 77 pp.

Davis, T. R. H. and Sutherland, A. J., 1983. ‘Extremal hypotheses for river behavior.’ *Water Resources Research* 19, 141-148.

Dodds, D. G. and Patton, D. R., 1968. Wildlife and Land use Survey of Luangwa Valley, FAO, Rome.

Drystal, A.R., Johnson, R.L., Moore, T.A. and Thieme, J.G., 1972. ‘Outline of the geology of Zambia', *Geologie en Mijnbouw*, 15, 263-276.

Dudley, R. W., 2004. ‘Hydraulic-geometry relations for rivers in coastal Central Maine.’ *Scientific Investigations Paper 2004-5042. US Geological Survey*, Augusta, Maine, 2004.

Eaton, B.C., 2010. ‘Hydraulic geometry: empirical investigations and theoretical approaches.’ www.geog.ubc.ca/~beaton/Literature/Eaton-2010-TifG.pdf.

FAO, 1968. Multipurpose Survey of the Kafue River basin, Zambia, Rome.

Ferguson, R.I., 1986, ‘Hydraulics and hydraulic geometry', Progress *in Physical Geography* 10, 1-31.

Giardino, J.R., 1973, 'Geomorphology and soils of the Luangwa Valley', *Zambia Geographical Association, Conference Handbook: Eastern Province,* Lusaka, p. 30-47.

Gilvear, D., Winterbottom, S. and Sichingabula, H., 2000. ‘Character of channel change and meander development: Luangwa River, Zambia.’ *Earth Surface Processes and Landforms* 25, 421-436.

Hey, R.D., 1978. 'Determinate hydraulic geometry of river channels'. *Journal of Hydraulic Division of America Society of Civil Engineers*, 104, 869-885.

Hickin, E. J., 1995. Hydraulic geometry and channel scour, Fraser River, British Columbia, Canada’, In: Hickin, E.J. (ed.) River Geomorphology. John Wiley & Sons, 155-167.

Huang, H. Q. and Nanson, G., 1995, 'Hydraulic geometry and bank strength on selected streams in southeastern Australia: Abstract', *International Association of Geomorphologists, Southeast Asia Conference, Programme with Abstracts,* 18-23 June, 1995, National University of Singapore & Nanyang Technological University, Singapore, p. 47.

Huang, H. Q. and Nanson, G. C., 2000. ‘Hydraulic geometry and maximum flow efficiency as products of the principle of least action.’ *Earth Surface Processes and Landforms,* 25, 1-16.

Karabasis, E. N., 1988. The morphology of the Kakumbi concave bank bench on Luangwa River. Undergraduate dissertation, Geography Department, University of Zambia, Lusaka, 54 pp.

Knighton, A.D., 1975. 'Variations in at-a-station hydraulic geometry'. *American Journal of Science*, 275, 186-218.

Langbein, W.B., 1964. 'Geometry of river channels'. *Journal of Hydraulic Division America Society of Civil Engineers*, 90, 301-312.

Langbein, W.B., 1965, 'Geometry of river channels: Close of discussion', Journal *of Hydraulic Division of America Society of Civil Engineers*, 91, 297-313.

Leopold, B. and Langbein, W.B., 1962. 'The concept of entropy in landscape evolution', U. *S. Geological Survey Professional Paper*, 500-A, 20 pp.

Leopold, B. and Langbein, W.B., 1964. ‘Quasi-equilibrium states in channel morphology.’ *American Journal of Science* 262: 782-794.

Leopold, L.B., and Maddock, T., 1953. 'The hydraulic geometry of stream channels and some physiographic implications', U.S. *Geological Survey Professional Paper,* 252, 1-57.

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. *Fluvial Processes in Geomorphology*. Freeman, San Francisco.

Mäckel, R., 1971, ‘The physiographic regions of Zambia', *Geographical Association Magazine*, Lusaka, 19, 1-20.

Mäckel, R., 1985. ‘Dambos and related landforms in Africa - an example for the ecological approach to tropical geomorphology.’ *Z. Geormorph. N. F. Suppl.* -Bd 52, 1-23.

Mäckel, R., 1986. ‘Dambo environments of the Central Plateau Region of Zambia.’ *Zambia Geographical Journal,* 36, 28-47.

Maddock, T., 1969. 'The behavior of straight open channels with movable beds', U.S. *Geological Survey Paper Professional Paper*, 622-A, 70 pp.

Money, N.J., 1972. ‘An outline of the geology of western Zambia', Records: *Geological Survey of Zambia*, 12, 103-123.

Morisawa, M., 1968. Streams: their dynamics and morphology. McGraw-Hill, New York, 175 pp.

Osterkamp, W.R., Lane, L.J., and Foster, G.R., 1983. ‘An analytical treatment of channel-morphology relations', U.S. *Geological Survey Professional Paper,* 1288, 21 pp.

Park, C.C., 1977. ‘World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations', *Journal of Hydrology,* 33, 133-146.

Parker, G., 1979. Hydraulic geometry of active gravel rivers. *Journal of Hydraulic Division (Proceeding American Society Civil Engineers),* 105 (HY9), 1185-1201.

Phillips, J.D., 1990, ‘The instability of hydraulic geometry', Water *Resources Research,* 26, 739-744.

Ponton, J. R., 1972, Hydraulic geometry in the Green and Birkenhead river basins, British Columbia. Mountain Geomorphology: Geomorphological Processes in the Canadian Cordillera, pp. 151-160, Tantalus Research Limited, Vancouver, Canada.

Richards, K.S., 1973, ‘Hydraulic geometry and channel roughness: A non-linear system', American *Journal of Science*, 273, 877-896.

Richards, K. S., 1976. ‘Complex width-discharge relations in natural river sections.’ *Geological Society of America Bulletin,* 87, 199-206.

Richards, K.S., 1982. *Rivers: form and process in alluvial channels*, Methuen, London.

Rhoads, B. L., 1991. ‘A continuously varying parameter model of downstream hydraulic geometry.’ *Water Resources Research*, 27, 8, 1865-1872.

Rhodes, DID, 1977. 'The b-f-m diagram: Graphical representation and interpretation of at-a-station hydraulic geometry'. *American Journal of Science,* 277, 73-96.

Rhodes, D.D., 1978. 'Discussion: worldwide variation in hydraulic geometry exponents of stream channels: An analysis and some observations'. *Journal of Hydrology,* 39, 193-197.

Rhodes, D.D., 1987. 'The b-f-m- diagram for downstream hydraulic geometry'. *Geografisca Annaler,* 69A, 147-161.

Riley, S. J., 1978. ‘The role of minimum variance theory in defining the regime characteristics of the lower Namoi-Gwydir basin.’ *Water Resources Bulletin,* 14, 1-11.

Schumm, S.A., 1960. 'The shape of alluvial channels in relation to sediment type', *U.S. Geological Survey Professional Paper,* 352-B, 15 pp.

Sharma, T. C., 1984. Characteristics of runoff processes in the Upper Kafue basin. National Council for Scientific Research, Water Resources Report, No. 25, Lusaka.

Sichingabula, H. M., Walling, D. E., Collins, A. L. and Leeks, G. G. L., 2007. ‘Suspended sediment transport characteristics of Upper Kaleya River, southern Zambia.’ Paper presented to the 8th WATERNET/WARFSA/GWP-SA Symposium: IWRM Concept to Practice, 31 October – 2 November 2007, Lusaka, Zambia.

Sichingabula, H. M., 1999b. ‘Clastic sediment flux into the Indian and Pacific oceans by rivers in central southern Africa and western Canada.’ Proceedings of the Hydrological and Geochemical Processes in Large Scale River Basins, 15-19 November 1999, Manaus, Brazil, 7 pp.

Sichingabula, H. M., 1999a. Analysis and results of discharge and sediment monitoring activities in the southern Lake Tanganyika basin: Final Report. Lake Tanganyika Biodiversity Project funded by UNDP/GEF/RAF/G32. http://www.ltbp.org/FTP/SSS4.PDF.

Sichingabula, H. M., 1996. Estimation of contemporary suspended sediment loads on Kafue and Luangwa Rivers, Zambia. In: B. W. Webb (ed.) Erosion and Sediment Yield: Global and Regional Perspectives, Poster booklet report, (*Proceedings, Exeter International Symposium*, July 1996), pp. 96-99.

Singh, V. P. 2003. ‘On the theories of hydraulic geometry’, *International Journal of Sediment Research*, 18, 3, 196-218.

Slingerland, R., 1981, 'Qualitative stability analysis of geologic systems with an example from river hydraulic geometry', *Geology* 9, 491-493.

Smith, T. R., 1974. ‘A derivation of the hydraulic geometry of steady-state channels from conservation principles and sediment transport laws.’ *Journal of Geology*, 82, 98-104.

Stewardson, M., 2005. ‘Hydraulic geometry of stream reaches.’ *Journal of Hydrology* 306, 97-111. http:dx.doi.org/10.1016/j.jhydro.2004.09.004.

Thorne, C.R., 1979, 'Bank processes, bed movement and planform development in a meandering river’. In: D. D. Rhodes and G. P. Williams (Eds.). Adjustments of the Fluvial System. Kendall Hunt, Dubuque, Iowa, pp. 117-137.

Thornes, J. B., 1970. ‘The hydraulic geometry of stream channels in the Xingu-Araguaia headwaters.’ *The Geographical Journals*, 136, 376-382.

Thornes, J.B., 1977. ‘Hydraulic geometry and channel change', In: K.J. Gregory, River Channel Change. John Wiley, Chichester, p. 91-100.

Wharton, G., 1995. ‘The channel-geometry method: Guidelines and applications.’ *Earth Surface Processes and Landforms* 20, 649-660.

White, G., 1973. Soil resources of Eastern Province. Zambia Geographical Association Conference Handbook Series, Eastern Province, Lusaka, pp. 54-65.

Wilcock, D.N., 1971. 'Investigations into relations between bed transport and channel shape.’ *Geological Society of America Bulletin*, 82, 2159-2176.

Wolman, M. G., 1955. The natural channel of Brandywine Creek, Pennsylvania. U. S. Geological Survey Professional Paper 271, Washington, D. C.

Whitlow, R., 1984. ‘A survey of Dambos in Zimbabwe.’ *Zimbabwe Agricultural Journal* 81, 4, 129-138.

Whitlow, R., 1985. ‘Dambos in Zimbabwe: a review.’ *Z. Geomorph. N. F., Suppl.* - Bd 52, 115-146.

Wolman, M.G., 1955. 'The natural channel of Brandywine Creek, Pennsylvania', *U.S. Geological Professional Paper*, 271, 50 pp.

Young, C. T. and Song, C. C.S., 1979. ‘Theory of minimum rate of energy dissipation.’ *Journal of Hydraulic Division of American Society of Civil Engineering* 105 (HY7), 769-784.