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Small reservoirs depth-area-volume relationships in Savannah Regions of Brazil and Ghana

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Abstract: In the last years, hundreds of small reservoirs were built in the Savannah regions of Brazil and Ghana. They play an important role in supporting the local economies. The lack of technical information about the small reservoirs in these regions is endangering the sustainability of agriculture and the livelihood of farmers. The purpose of this study was to establish the volume-area-depth relationship for small reservoirs in the Brazilian and Ghana Savannah regions. Thus, a comprehensive field work was performed. In total, 28.5% and 39.0% of the total number of small reservoirs in the Preto River Basin in Brazil and in the Upper East Region of Ghana, respectively, were visited and measured. The results showed a good-fit for the depth-volume and area-volume relationships for both regions, with coefficient of determination, for both cases and both regions, higher than 0.93. The mean k and α_1 values were lower in Brazil as compared to Ghana and k_1 and α were higher. The values of the parameters presented great variability, indicating the importance of performing local measurements.

Key words: water resources, dams, bathymetry, storage-volume

Relação profundidade-área-volume em pequenos reservatórios localizados no Cerrado do Brasil e de Gana

Resumo: Nos últimos anos, centenas de pequenas barragens foram construídas na região do Cerrado do Brasil e de Gana. Eles são de fundamental importância para a economia local. A ausência de informações técnicas sobre eles, que é crucial para o processo de tomada de decisão sobre o planejamento e manejo de recursos hídricos em bacias hidrográficas, entretanto, está colocando em risco a sustentabilidade da agricultura e a qualidade de vida das comunidades rurais nessas regiões. O objetivo deste estudo foi estabelecer relações cota-área-volume para pequenas barragens na região do Cerrado do Brasil e de Gana. Para isto, foi realizado um levantamento bastante detalhado. No total, 28,5% e 29,0% do total de barragens existentes na bacia hidrográfica do Rio Preto e na região superior leste de Gana, respectivamente, foram visitados e avaliados. Os resultados indicaram um bom ajuste das relações cota-volume e área-volume para as duas regiões, com coeficiente de determinação superior a 0,93, para os dois casos e as duas regiões. Os valores médios de k e α_1 foram menores para as barragens do Brasil e os de k_1 e α maiores. Observou-se uma grande variabilidade dos parâmetros, indicando a importância de se realizar medidas locais.

Palavras-chave: recursos hídricos, barragens, batimetria, volume armazenado

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Introduction

Small reservoirs are a common form of water infrastructure encountered in areas, such as the Preto River Basin, a sub-catchment of the São Francisco watershed, Brazil, or the Upper East Region of Ghana, in the Volta Basin of West Africa. They provide water for a number of different uses, e.g. for dry season irrigation and livestock watering in Brazil, and, additionally, for fishing, building and domestic purposes in Ghana.

These reservoirs contribute to reducing the vulnerability of their basin inhabitants to drought and to improving their livelihoods. The reservoirs also have a significant effect on downstream flows, as they can provide a buffer from flooding by delaying and diminishing flash floods by temporarily storing the excess water (Poolman, 2005). They also help recharge groundwater aquifers, thereby increasing the base flow in the downstream part of the catchment area (Adwubi et al., 2009). The sustainability of the reservoirs in Brazil and Ghana, however, is being challenged by problems that directly affect the economic livelihoods and economic development of their basin inhabitants.

In Brazil and Ghana, hundreds of small reservoirs were built in the last few decades, to help improve irrigated agriculture in the region. They are an important part of water resource management and their development needs to be pursued in a strategic manner and requires planning of water resources. However, efficient water management and sound reservoir planning and management are hindered by inadequate knowledge of their number, storage capacity and spatial distribution in the basin.

Arrays of small reservoirs can potentially have a large impact on the hydrology and the ecology of the surrounding environment. They have a significant effect on the water yield of the strategic reservoir, and this effect is simulated to even increase under disadvantageous climate changes (Krol et al., 2011). Information about reservoir locations and storage volumes is critical for decision-making processes regarding planning and management of water resources. In the recent past, the issue of small reservoirs inventories and regional storage volume assessment has been addressed in a number of different regions. In Brazil, Rodrigues et al. (2007) carried out an inventory and classification of reservoirs by means of remote sensing using three Landsat ETM images taken in 2005 and detected 253 small reservoirs only in the Preto River Basin, which represents 1.6% of the São Francisco Basin area. In the Upper East Region of Ghana, Liebe et al. (2005) mapped 154 small reservoirs using two Landsat ETM images from 1999, and tested the suitability of ENVISAT ASAR, a C-band radar, and ALOS PALSAR, an L-band radar, to measure and monitor small reservoir extents (Liebe et al., 2009; Annor et al. 2009). These satellite based inventories, however, only provide information on the number, location, and the surface extents of small reservoirs.

Despite the large number of poorly-defined reservoirs in the Preto River Basin and Upper East Region of Ghana, information about the reservoirs is still a major problem. Liebe et al. (2009) developed a procedure to test a runoff model by remotely sensing reservoir sizes over time and concluded that regarding the applicability of the method used to derive runoff volumes, the most crucial question is whether regional relations can be found that relate surface areas to stored volumes. Presently, we cannot predict such relations on the basis of readily available global data and must rely on bathymetric surveys.

Area-capacity curves are of the most important physical characteristics of dams' reservoirs. These curves are used for reservoir flood routing, dam operation, determination of water surface area and capacity corresponding to each elevation, reservoir classification and prediction of sediment distribution in reservoirs. As a result, obtaining the area-capacity equations has great significance from a practical aspect (Haghiabi et al., 2013). Besides this, these relations are site specific, and are usually derived from a detailed bathymetry map.

To be able to assess the sedimentation rate or to determine sustainable water withdrawal rates, the water level – volume – reservoir area or stage curve relationships provide invaluable information.

While the small reservoir depth-area-volume relationship is important information for water resource planning and managing, hydrology and modeling, it is laborious, time consuming and costly to obtain them, specifically in areas with large number of this infrastructures, as is the case of Brazil and Ghana.

The main objective of this study was therefore to establish volume-area-depth relationships for small reservoirs located in the Preto River Basin, in the Brazilian Savannah, and in the Upper East Region of Ghana. This information will be very useful for planers and can help to improve water management in those regions.

Materials and Methods

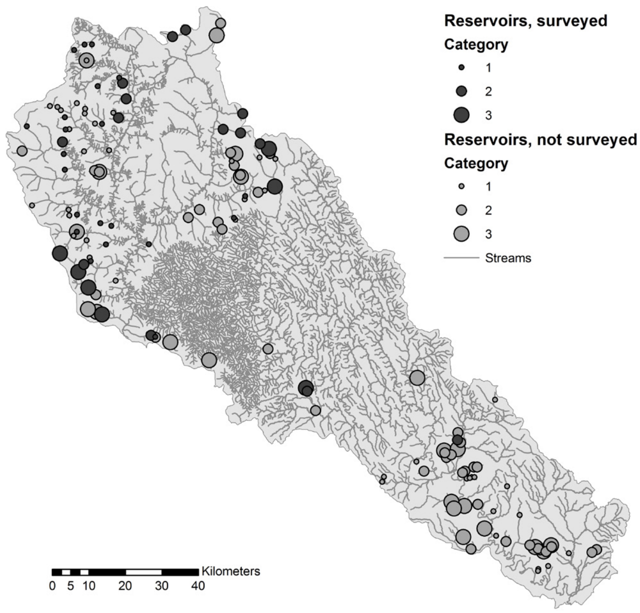
The study area in Brazil was the Preto River Basin. Located in the central portion of Brazil, on the western side of the Middle portion of the São Francisco Basin, the drainage area of basin is roughly 10,500 km². The basin traverses two states, Minas Gerais and Goiás, as well as the Federal District, and encompasses 10 municipalities (6 in Minas Gerais, 4 in Goiás). The basin has a tropical wet and dry climate, with a long dry season lasting from May to September, and a rainy season that usually starts around October and ends in April. The mean annual rainfall is around 1,200 mm, of which 85% occurs during the rainy season. The length of the dry season contributes to various problems with forest fires, water shortages and conflicts, and insecure food production. Viable agriculture in the basin is only possible through irrigation, which depends on the water stored in the small reservoirs.

The study area in Ghana was the Upper East Region. The basin drainage area is roughly 8,842 km²; it is located in the White Volta Basin, bordering Burkina Faso and Togo. It is inhabited by one million people and is amongst the poorest of Ghana's Regions. Agriculture plays a major role for both income generation and subsistence, and the pressure on water resources increases due to steep population growth. The semi-arid climate is characterized by a three month, monomodal rainy season. The great variability of precipitation, however, frequently leads to crop loss in rainfed agriculture. Also, ninety percent of the Region's total rainfall (986 mm) occurs as thunderstorms, originating from squall lines (Eldridge, 1957; Hayward & Oguntoyinbo, 1987; Friesen, 2002), in which rainfall intensities often exceed the soil's water holding capacity causing surface runoff, without replenishing soil moisture and groundwater. Small reservoirs are therefore an important form of water storage that allows the population to generate a more dependable income from dry season irrigation. Like in Brazil, the small reservoirs are relatively shallow due to the flat topography of the region.

For the Preto River Basin the inventory and classification of reservoirs was conducted by means of remote sensing using three Landsat ETM images taken in 2005 (Rodrigues et al., 2007). In the Basin, 252 small dams were identified with reservoir surface areas varying between 1 to 413 ha. In this classification good user accuracy was achieved, with just one misclassification (that of a lagoon listed as a reservoir) detected in the 51% of reservoirs visited. The satellite and ground based surface areas were compared and used as a second quality indicator. A questionnaire-based and semi-structured interview was carried out with farming households prior to each reservoir survey, with questions focused on reservoir characteristics such as the existence of technical information (area, depth, maps, etc.), maintenance, age, purpose, etc. (Rodrigues et al., 2012). The initial database consisted of 252 small reservoirs, but only those with surface areas between 1 and 50 ha were considered. There were a total of 147 small reservoirs in this size range (Figure 1A).

For information purposes, the reservoirs were split into three categories (Figure 1A): Category 1, with areas of 1-3 ha (68 reservoirs), Category 2 with areas of 3-10 ha (51 reservoirs), and Category 3, with area of 10 to 50 ha (28 reservoirs). To have an extensive sample set and to ensure sufficient

A.



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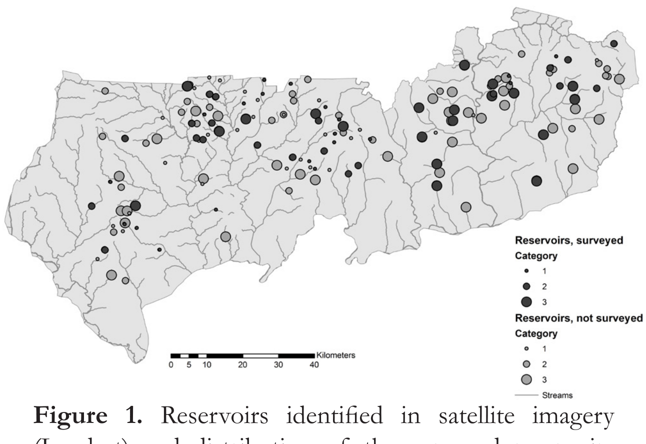

Figure 1. Reservoirs identified in satellite imagery (Landsat) and distribution of the surveyed reservoirs by surface area category (Category 1: 1- 3 ha; Category 2: 3-10 ha; and Category 3: 10-50 ha). (A) Preto River Basin, Brazil; (B) Upper East Region of Ghana

coverage for finding surface area-volume relationships, 42 out of the 147 (28.5%) of the total amount of small reservoirs were evaluated. This represented 29.4% of the reservoirs of Categories 1 and 2, and 25.0% of Category 3. The selected reservoirs were visited and measured during three fieldwork periods that were conducted from March to April and October to November of 2006 and from March to May of 2007.

In the Upper East Region of Ghana, an inventory of small reservoirs was carried out through a classification of two Landsat ETM scenes from October 13 and November 7, 1999, i.e. at the end of the rainy season of a wet year where the reservoirs are expected to be filled to capacity (Liebe et al., 2005). In total, 540 water bodies were detected within the region, of which 154 reservoirs within the size ranged between 1-35 ha were selected for further analysis (Figure 1B). As in the classification of reservoirs in the Sao Francisco Basin, the user accuracy of the reservoir maps was high. All the 61 reservoirs visited existed, indicating good user accuracy.

In the Upper East Region of Ghana, similarly to the approach used in the Preto River Basin, the 154 reservoirs within the target range (1-35 ha) were categorized into three approximately equally sized categories (Figure 1B). Category 1 has 51 reservoirs in the range of 1–2.79 ha, Category 2 contains 53 reservoirs between 2.88 and 6.93 ha, and Category 3 has 50 reservoirs ranging from 7.02 to 35 ha. A total of 61 reservoirs (39.6% of total population) was randomly selected within the three categories (20 reservoirs each from Categories 1 and 3, and 21 reservoirs from Category 2) to capture the variance over the different reservoir sizes. The bathymetrical surveys were conducted between December 2002 and February 2003. At this time of the year, the reservoirs were not filled to capacity anymore. Therefore, in addition to the bathymetric survey, the difference between the actual water level and the spillway level was recorded.

The general idea behind depth measurements in reservoirs with the aim of adequate volume estimation is based on finding its deepest point from which it can be interpolated to the shores. The large number of points taken between the deepest point and the shoreline yield an accurate representation of the reservoir shape (Liebe et al., 2005). The collection of the depth data was not done according to a predefined grid. Each reservoir was measured according to unique judgment taking into account the local variation and characteristics. The shape and size of the reservoir surface area were determined by walking around each reservoir with a handheld GPS and taking large numbers of points along the shoreline. Following that step, bathymetric maps were compiled. Water depths were measured in several places inside the reservoirs using a plummet from a boat, with each measurement accompanied with GPS coordinates. Depth measurements of reservoirs were conducted to estimate the volume of a reservoir; the measurement entails finding a reservoir's deepest point from which it can be interpolated to the shores. Care was taken to achieve good coverage of points well spread over the reservoir while focusing on the areas closest to the dam wall, where the deepest points are generally found. The biggest problem turned out to be navigation due to wind-induced boat drift.

In order to derive the storage volumes of the surveyed reservoirs and the volume-area-depth relationships, a 3D-Model was created for each of the 103 reservoirs' (42 in Brazil and 61 in Ghana), volume and surface area were calculated for different water depths at 5 cm depth intervals, using the script contaarea.bas, developed by Golden® software.

The volume of reservoirs can be expressed as a function of their surface area, which allows for storage volume assessment from satellite imagery, or as a function of depth, which is often used in conjunction with stage data measured at the reservoirs. Both area-volume and depth-volume curves for reservoirs can be explained with power functions of the form

$$V = \theta X^{\sigma}$$

where:

V - stored volume, m^3

X - depth, m or surface area, m^2

θ - equal k if X = depth (H) or k1 if X = surface area

σ - equal α if X = depth or α1 if X = surface area

The equation is valid for 0 ≤ depth (H) ≤ maximum depth (MD) and 0 ≤ surface area ≤ maximum surface area (MSA).

Results and Discussion

Figure 2 shows a 3D-model of a reservoir (Category 3) in Ghana, with the distribution of the depth measurements and the result of the interpolation. It was created from 502 GPS-readings delineating its outline and 126 depth measurements. The inset in the top right corner shows the distribution of the depth measurements, which cluster most densely in close range to the

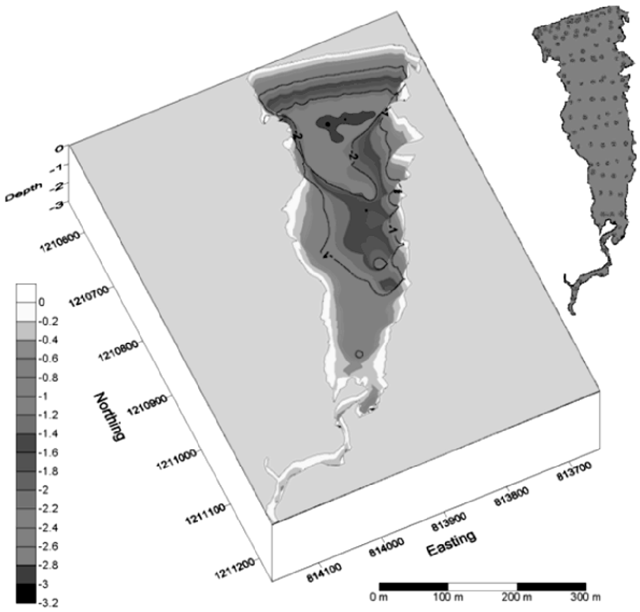

Figure 2. 3D-model for one reservoir in Ghana. The inset in the top right corner shows the distribution of the depth measurements

dam wall (top edge) to capture its deepest point (3.10 m). The remaining parts of the reservoir are evenly covered. The reservoir had an area of 9.01 ha, and contained 100,435 m³ of water at the time of observation.

Figure 3 shows the correlation between logarithms of depth (H) and volume (Figure 3A) and logarithms of surface area and volume of a reservoir in Brazil (Figure 3B). The linearity observed for this specific reservoir was the same verified in all reservoirs evaluated in both regions. For Brazil, R^2 was larger than 0.97 and for Ghana it was greater than 0.95. Despite the variety of reservoir shapes, the derived equations for all reservoirs, independent of size, for the whole Preto River Basin and the Upper East Region of Ghana fitted the observed data quite well, which give great confidence in their application. This information has importance in hydrology. Besides water level-volume, reservoir area or stage curve relationships, multi temporal comparison between bathymetries can be used as an indicator for environmental changes like lake or reservoir sedimentation. From this information, lake ecosystem functioning, life times of reservoirs or erosion – sedimentation rates of catchments can be derived (Dost & Mannaerts, 2008).

Locations and values for the parameters k and α, of the relationships between depth and volume, and for k1 and α1, of the relationships between surface area and volume, for the reservoirs in the Preto River Basin, Brazil, are reported in Table 1 and for the Upper East Region of Ghana in Table 2.

The equation used to represent the depth-volume relationship is based on the fact that small reservoirs resemble an inverted pyramid. The coefficient k represents the openness of the pyramid. The more open and flatter the valley, the larger is k. Thus, one expects to get high k values in wide and open alluvial valleys (Molle, 1994). According to same author, α, defined as shape coefficient, is related with the hillside concavity.

The general shapes of the reservoir curves as shown in Fig. 3 represents the expected curves for small reservoirs and is similar to curves obtained by other authors, like Sawunyama et al. (2006), for area-volume, and Choodegowda (2009), for depth-volume.

Figure 4 presents a box plot of k and α and of k1 and α1. It can be observed that the average k and α1 values were lower in Brazil than in Ghana and the k1 and α values were higher. The analysis of the box length gives an indication of data variability. It can be noted, e.g. that the parameter α is more variable than k and that this last one has about the same variability for the reservoirs in Brazil and Ghana.

For the Preto River Basin, Brazil, the values of k varied from 18.12 to 36855.30, with a mean value of 3146.77 and a coefficient of variation (CV) of 2.04, and α from 1.58 to 3.75, with

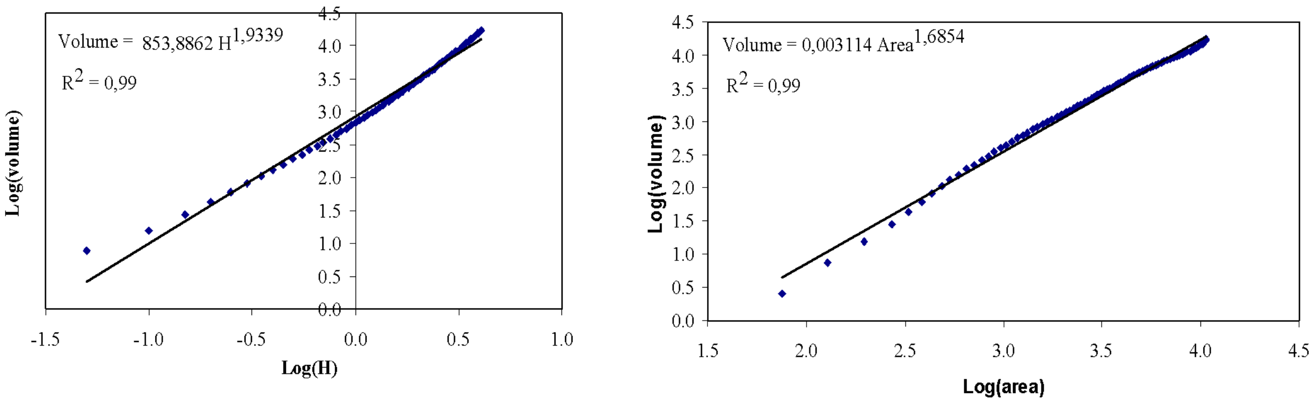

Figure 3. Correlation between logarithms of depth (H) and volume, (A), and logarithms of area and volume, (B), for one reservoir in Brazil

Table 1. Locations, maximum depth (MD), measured surface area (MSA), and coefficients k and α and k1 and α1 of the relationships depth-volumes and area-volumes, respectively, for the reservoirs in the Preto River Basin, Brazil

ID	Coordinate (UTM)		$V = k\ Depth^{\alpha}$*			$V = k1\ area^{\alpha 1}$**		
			Parameter		MD	Parameter		MSA
	Leste (mE)	Norte (mN)	k	α	(m)	k1	α1	(ha)
1	282414	8235713	27.62	3.13	8.10	0.076401	1.34	2.24
2	290539	8238342	36855.30	1.98	3.85	0.000020	1.91	29.68
3	279320	8229778	1268.24	2.58	3.20	0.008185	1.47	2.45
4	255992	8222586	529.91	2.73	3.85	0.010368	1.49	2.27
5	256594	8197745	504.43	2.87	6.30	0.019597	1.41	7.36
6	257728	8197358	222.48	2.94	7.45	0.038159	1.36	2.84
7	340598	8169196	3098.85	2.51	4.15	0.001589	1.64	3.93
8	299050	8183349	5655.88	2.46	3.95	0.002570	1.54	11.83
9	299360	8182498	4385.31	2.34	1.80	0.001994	1.57	2.32
10	235537	8275584	18.12	3.07	8.70	0.059832	1.24	2.04
11	245719	8227592	188.32	3.01	3.90	0.034698	1.37	1.09
12	238381	8277034	853.89	1.93	4.05	0.008572	1.69	1.35
13	248811	8266511	596.07	2.96	9.25	0.014178	1.48	8.54
14	249781	8262247	5874.89	2.96	2.90	0.003627	1.48	6.54
15	247664	8257058	2084.97	2.31	7.15	0.004520	1.55	10.52
16	232314	8250484	3238.17	2.08	7.90	0.000559	1.78	8.11
17	232950	8257226	3221.07	2.21	1.85	0.000839	1.72	1.35
18	233167	8253877	449.68	2.59	2.90	0.022756	1.39	1.14
19	236237	8225957	1019.30	2.88	6.60	0.009032	1.48	14.50
20	236300	8230664	376.96	2.90	5.80	0.014129	1.47	3.56
21	243155	8255396	163.95	3.75	3.80	0.044761	1.29	3.10
22	232680	8247183	631.39	2.53	4.50	0.004967	1.60	2.41
23	232979	8242909	402.81	2.45	4.05	0.007303	1.59	1.80
24	242706	8228324	139.70	2.90	4.60	0.030165	1.42	1.10
25	240407	8277087	114.58	2.74	3.10	0.020559	1.51	1.00
26	247841	8268007	29.07	3.08	7.90	0.069615	1.37	1.55
27	241968	8265665	1375.62	1.68	3.95	0.018733	1.46	1.37
28	222525	8254732	908.45	2.91	2.95	0.016577	1.39	2.75
29	231608	8220089	936.70	2.93	10.25	0.013113	1.43	35.07
30	238186	8217061	3803.65	1.84	5.85	0.000091	1.99	4.33
31	244218	8222545	1880.62	2.42	3.90	0.002254	1.63	2.95
32	236665	8215014	10997.65	2.04	5.90	0.000252	1.76	19.17
33	239421	8210772	134.96	3.22	7.75	0.043995	1.35	7.06
34	243132	8203434	2387.26	2.64	6.75	0.003197	1.56	1.46
35	281145	8252948	883.08	2.66	7.20	0.009710	1.48	9.27
36	281720	8258211	1415.47	2.56	3.60	0.009447	1.45	3.46
37	276342	8253916	239.72	3.17	5.65	0.023405	1.41	3.19
38	288896	8248595	13915.54	2.40	2.55	0.003331	1.45	20.86
39	286472	8249987	419.76	2.96	5.90	0.015527	1.44	4.25
40	266090	8281024	15984.53	1.79	1.85	0.000079	1.85	6.05
41	262472	8279203	3111.72	2.98	3.00	0.006937	1.43	7.89
42	240028	8218028	1818.86	2.10	2.70	0.001334	1.72	1.05

* Range that the equation is valid: 0 ≤ depth ≤ MD
** Range that the equation is valid: 0 ≤ area ≤ MSA

a mean value of 2.61 and a CV = 0.17. In the Upper East Region of Ghana the values of k varied from 377.88 to 26413.39, with an average of 5547.11 and a CV = 0.98, and a α from 1.83 to 4.08, with a mean value of 2.59 and a CV = 0.19. k1 varied from 0.0000025 to 0.0268534, with a mean value of 0.0030960 and a CV = 1.60, and from 0.0000196 to 0.1739402, with an average of 0.0187054 and a CV = 1.62 in Upper East Region of Ghana and Preto River Basin, Brazil, respectively. α1 varied from 1.18 to 2.23, with an average of 1.67 and a CV = 0.12, and from 1.24 to 1.99, with an average of 1.52 and a CV = 0.11 in Upper East Region of Ghana and Preto River Basin, Brazil, respectively.

The results suggest that these relationships are region-specific and as expected depend on several factors like topography, valley shape and geology of the area, being difficult to make direct comparison of the results obtained in this study with other results. The parameters values of the equations area-volume are in the same order of magnitude of the equations obtained by Meigh (1995) that using topographic maps obtained a power relationship between capacity of the reservoir and its surface area measured with k1 = 0.0738 and α1 = 1.25 and R^2 = 0.93. The values are also comparable in order of magnitude to the ones obtained by Sawunyama et al. (2006). They evaluated 12 small reservoirs and developed

Table 2. Locations, maximum depth (MD), measured surface area (MSA), coefficients k and α and k1 and α1 of the relationships depth-volumes and area-volumes, respectively, for the reservoirs in the Upper East Region of Ghana

ID	Coordinate (UTM)		V = k Depth$^{\alpha}$*			V = k1 area$^{\alpha 1}$**		
			Parameter		MD	Parameter		MSA
	Leste (mE)	Norte (mN)	k	α	(m)	k1	α1	(ha)
1	808666	1222944	13483.8	3.01	1.32	0.00007	1.87	0.70
2	795493	1217460	2730.5	2.15	4.32	0.00073	1.75	1.63
3	727286	1216323	7717.6	2.28	3.81	0.00042	1.71	1.14
4	795959	1215457	664.2	2.83	1.83	0.00606	1.54	2.13
5	734728	1215274	2882.4	2.46	4.40	0.00053	1.75	1.70
6	726856	1212420	3235.7	2.40	1.93	0.00177	1.61	0.66
7	721602	1209702	2353.9	2.41	2.68	0.00539	1.53	0.93
8	744373	1208691	3204.8	2.00	4.32	0.00041	1.80	3.70
9	710645	1206619	2355.9	2.27	1.90	0.01132	1.45	0.55
10	748198	1205183	1972.3	2.20	3.09	0.03011	1.36	1.89
11	747011	1201216	5501.1	2.15	3.99	0.00089	1.68	1.65
12	756798	1199663	325.2	3.57	3.43	0.17527	1.10	3.99
13	746797	1198798	591.8	3.05	2.47	0.16338	1.15	0.53
14	739816	1193446	2072.4	2.94	3.93	0.00260	1.56	1.28
15	741419	1191323	5542.8	1.94	2.12	0.00151	1.63	0.79
16	775396	1186545	1804.7	2.21	3.69	0.27580	1.11	6.20
17	713827	1179839	1356.6	2.94	4.29	0.00762	1.46	1.75
18	688370	1175718	5754.7	2.17	3.50	0.00041	1.74	1.44
19	691734	1174685	5487.0	2.16	3.42	0.00119	1.61	1.73
20	698123	1168570	4229.3	2.48	1.92	0.00205	1.58	0.87
21	824766	1226534	17886.8	2.18	4.86	0.00030	1.68	5.79
22	811944	1221972	5846.4	2.39	1.37	0.00016	1.82	2.11
23	806979	1219684	5565.9	5.20	3.97	0.00214	1.51	4.16
24	809747	1214621	4127.5	2.58	3.21	0.00073	1.67	0.28
25	819975	1213972	9253.2	1.82	3.62	0.00010	1.89	4.17
26	791198	1212410	1253.9	2.72	3.38	0.04791	1.30	2.21
27	712078	1212321	1125.0	2.52	4.10	0.04816	1.32	2.81
28	713763	1211609	12642.5	2.05	5.76	0.00031	1.73	1.89
29	742444	1204817	1422.4	2.82	2.63	0.27273	1.11	4.79
30	712708	1204194	16584.0	2.20	4.07	0.00026	1.71	4.38
31	707126	1204072	1223.7	3.23	3.03	0.07077	1.24	4.13
32	708415	1199962	6235.6	2.03	3.95	0.00021	1.82	8.85
33	688480	1199804	2731.7	2.43	2.49	0.00309	1.57	1.60
34	710230	1199519	4168.8	2.10	3.69	0.00289	1.59	3.38
35	725398	1198001	1663.3	2.79	4.18	0.08351	1.23	3.05
36	744002	1196323	11469.3	2.04	3.94	0.00027	1.75	4.11
37	735250	1194575	979.1	3.14	3.76	0.01013	1.44	5.26
38	753491	1192236	7689.9	2.17	4.64	0.00056	1.71	5.83
39	750774	1189893	6724.4	1.99	4.45	0.00037	1.76	6.34
40	679198	1180798	3319.7	2.84	2.85	0.00309	1.52	2.53
41	682879	1168466	639.0	3.06	3.07	0.04382	1.32	3.45
42	783084	1220478	3560.6	2.59	7.07	0.00260	1.56	4.25
43	791023	1215197	12479.1	2.35	5.14	0.00024	1.73	5.46
44	813326	1214533	5100.0	2.55	5.19	0.00359	1.51	11.45
45	705874	1214557	5579.3	2.25	4.86	0.00031	1.78	6.78
46	796886	1212593	7277.5	2.42	5.49	0.00242	1.53	5.09
47	790733	1211798	5365.4	2.61	3.74	0.00365	1.50	4.95
48	813854	1210812	4413.4	2.87	4.48	0.00931	1.41	9.01
49	770414	1208489	983.1	3.35	4.93	0.00711	1.45	19.50
50	780248	1207916	3386.8	2.78	5.16	0.00273	1.54	13.53
51	741608	1206798	20989.6	2.31	5.37	0.00117	1.55	12.88
52	722162	1205295	2939.1	2.92	2.07	0.00461	1.48	7.66
53	779892	1204861	7005.9	2.41	4.30	0.00179	1.58	9.98
54	749273	1203258	9521.8	2.47	6.47	0.00099	1.60	19.41
55	714780	1201839	10871.0	2.25	3.02	0.00094	1.63	6.81
56	805151	1200921	9716.8	2.44	4.84	0.00121	1.59	13.78
57	771280	1200312	9407.7	2.58	4.44	0.00591	1.45	14.12
58	775371	1192650	2691.6	3.34	6.20	0.00107	1.59	38.28
59	684419	1187615	4595.9	2.81	2.47	0.00099	1.61	2.15
60	803216	1187820	3761.7	2.40	4.49	0.00372	1.54	10.49
61	691400	1180929	4158.3	2.24	4.99	0.00077	1.69	5.03

* Range that the equation is valid: 0 ≤ depth ≤ MD
** Range that the equation is valid: 0 ≤ area ≤ MSA

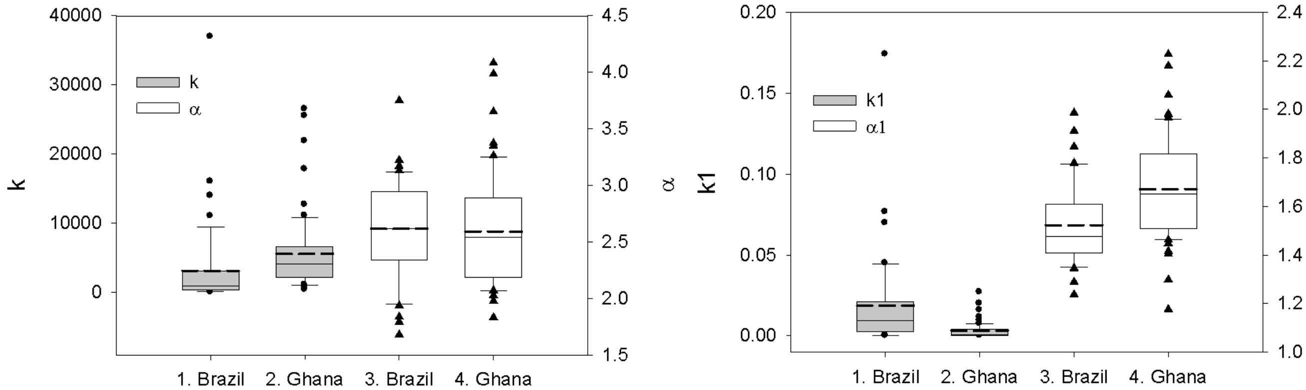

Figure 4. Box plot of k and α and of k1 and α1 parameters for small reservoirs in the Preto River Basin in Brazil (A) and for the Upper East Region of Ghana (B)

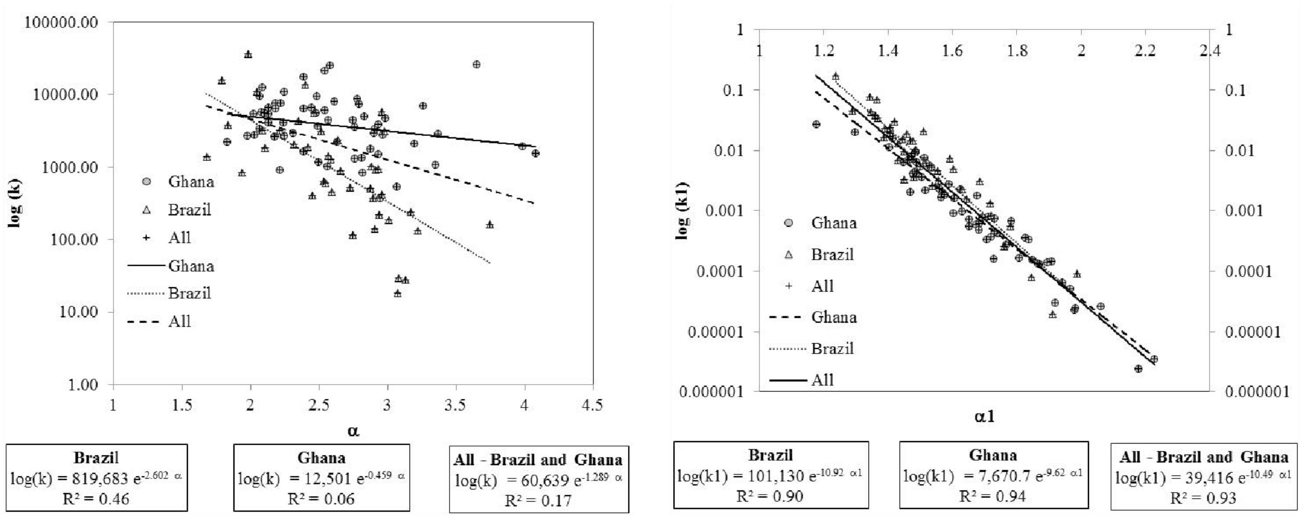

Figure 5. Log(k)-α, for the relationships between depth and volume, and log(k1)-α1, for the relationships between surface area and volume, for the reservoirs in the Preto River Basin, Brazil (A) and for the Upper East Region of Ghana (B)

relationship between capacity of the reservoir and their surface areas and obtained k1 values varying from 0.00017 to 0.078 and α1 from 1.26 to 1.67.

It would be of high interest for water planners to know how the parameters are correlated among themselves and to have a general equation that could be applied to Brazil and Ghana to estimate reservoir volumes based on both their depth and surface area. Figure 5 (A) and (B) presents the correlation between the parameters log(k) and α and parameters log(k1) and α1, respectively.

The first attempt was to find a correlation between the parameters for each study area separately. Following this, a general correlation between the parameters of Brazil and Ghana was investigated. The correlation obtained between log(k)-α, for the relationships between depth and volume, for both areas was not satisfactory (Figure 5A). This correlation was much better for the reservoirs in Brazil ($R^2 = 0.46$) than for those in Ghana ($R^2 = 0.06$).

On the other hand, the correlation between log(k1)-α1, for the relationships between surface area and volume, for both regions showed a very good-fit (Figure 5B). It indicates that a high potential exists to apply this relationship to estimate reservoir volumes based on their surface area. These results are very promising, once it shows the possibility for using remote sensing techniques to manage water of these infrastructures, which can contribute to minimize water conflicts in the region.

Future work should extend the analysis to a wider region and focus on the application of remote sensing to estimate variation in time and space of reservoir volumes based on their surface area. Liebe et al. (2009) state that satellite images for mapping the small reservoirs can be obtained from optical (i.e., Landsat, Spot, Aster, ISS, etc.) or radar satellite systems (ENVISAT, ERS, RADARSAT, etc.). Even though the technology exists, a need exists for improving the accuracy of extracting the water surface area from satellite images.

Information obtained from remote sensing could be used by planners in a type of alert system. For the irrigators, it will show the water available in the system and the risk of lack of water for irrigation. For the electric systems it will indicate the capacity of small reservoirs in a watershed to capture and retain water and their potential for flow regularization.

Conclusions

1. For all reservoirs evaluated in the Preto River Basin, Brazil, and in the Upper East Region of Ghana, a linearity between the logarithms of depth (H) and volume and logarithms of surface area (area) and volume was verified, with R^2 greater than 0.93 in all cases which can be used with confidence to plan and manage the water resources in those regions.

2. A great variability in the parameters of the relationships depth-volume was observed, indicating that the equations are site specific and as such their use should not be extrapolated.

3. A high correlation between the parameters of the relationships area-volume for the Preto River Basin, Brazil, for the Upper East Region of Ghana and for both regions together was observed, demonstrating that the generic power equation obtained can be used with confidence by planners to simulate volume in function of surface area in both places.

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