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Estimation of small reservoir storage capacities in a semi-arid environment
A case study in the Upper East Region of Ghana

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Abstract

In semi-arid regions at the margins of the Sahel, large numbers of small reservoirs capture surface runoff during the rainy season, making water available during the dry season. For the local population, small reservoirs are important water sources which help them cope with droughts. The lack of knowledge of the number of existing reservoirs, their distribution, and their storage volumes hinders efficient water management and reservoir planning. The authors have developed a simple method that allows the estimation of reservoir storage volumes as a function of their surface areas. This function is based on an extensive bathymetrical survey that was conducted in the Upper East Region of Ghana. In combination with satellite imagery, this function can be used determine and monitor the storage volumes of large numbers of small reservoirs on a regional scale.

Keywords: Small reservoirs; Drought mitigation; Water management; Dams; Ghana; Africa

1. Introduction

In the semi-arid regions of Northern Ghana, large numbers of small reservoirs dot the landscape. Reservoirs capture surface runoff during the rainy season making water available in the dry season. For the rural population in environments such as the Upper East Region of Ghana, the presence of a small reservoir is an important means of overcoming minor droughts. Efficient water management and sound reservoir planning are hindered by the lack of information about the functioning of these reservoirs. The reservoirs were built at different times by various agencies. Poor record keeping and the lack of appropriate institutional support result in deficiencies of information on the capacity, operation, and maintenance of these structures. As a first step towards understanding the impact these dams have on the availability of water in this area, the authors developed a simple method for estimating and monitoring the storage volumes of these reservoirs on the basis of their surface areas. The use of satellite imagery allows us to measure the reservoir surface areas and gives insight into the statistical (e.g. size, and frequency) and spatial distribution. The area based volume estimation is made possible because this region is morphologically and morphometrically regular. The reservoirs are located in the stream channels, and the morphometry of stream channels are a response to surface runoff characteristic of this area (Windmeijer and Andriesse, 1993).

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Damming these streams results in characteristic relationships between volumes to surface areas.

2. The study area

The Upper East Region of Ghana is situated in the center of the Volta Basin (Fig. 1, van de Giesen et al., 2002). The Upper East is inhabited by approximately one million people and has a population density of 96.5 inhabitants/km^2 (Asenso-Okyere et al., 2000). With a poverty incidence of 88% in 1998/1999, the Upper East has the largest portion of poor people of Ghana's ten regions (Ghana Statistical Service, 2000). The residents incomes are generated from rainfed and some irrigated agriculture. Population growth places pressure on scarce land and water resources. The scarcity of usable water resources is mainly due to the climate, especially the mode of rainfall. The Upper East's semi-arid climate is characterized by a three month, monomodal rainy season. Ninety percent of the Region's total rainfall (986 mm) occurs as thunderstorms, originating from squall lines (Eldridge, 1957; Hayward and Oguntoyinbo, 1987; Friesen, 2002). Rainfall intensities often exceed the soil's infiltration rates causing surface runoff, without replenishing soil moisture and groundwater. Small reservoirs help make better use of the rainfall by capturing runoff. This water can be used for domestic purposes and agricultural production. The small reservoirs' proximity to places of demand is another advantage that makes them an appropriate tool for drought mitigation.

3. Reservoir inventory with satellite imagery

Due to the lack of baseline data, our inventory of reservoirs was conducted by means of remote sensing. The reservoirs were classified with four Landsat ETM images. Three images were acquired at the end of the rainy season in 1999 (194/052-053—November 7, 1999;

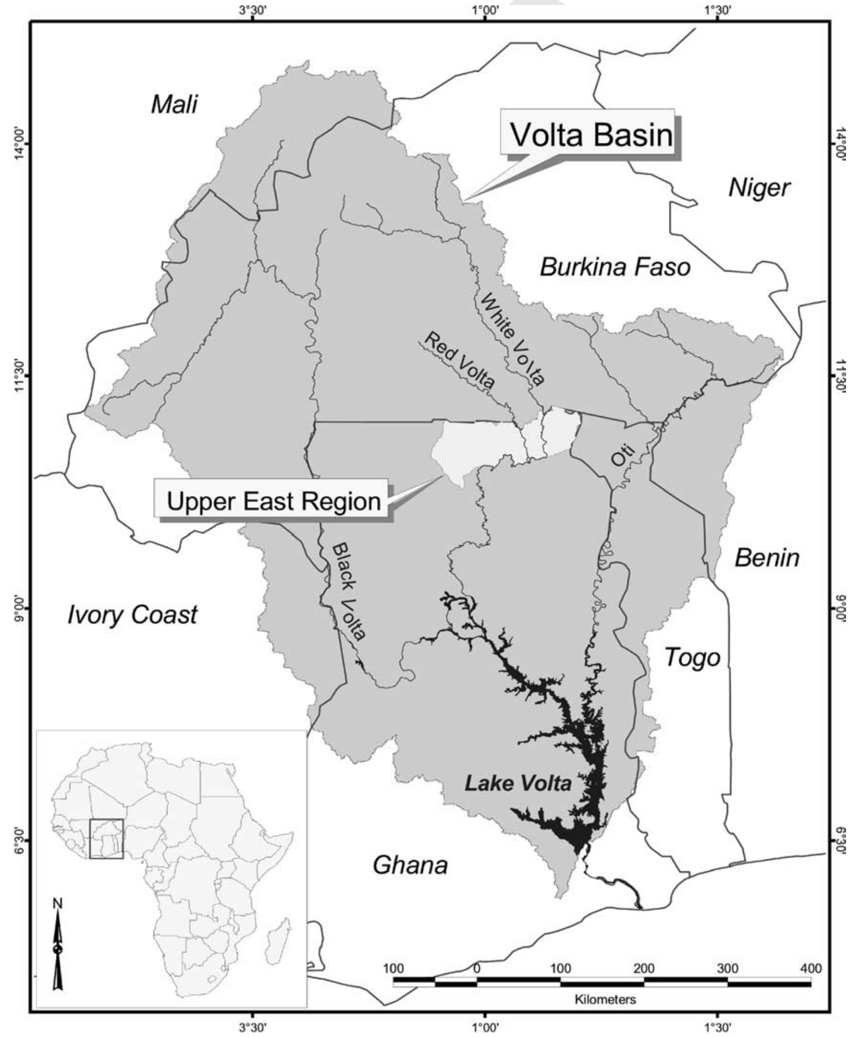

Fig. 1. The Upper East Region of Ghana within the Volta Basin, West Africa.

195/052—October 13, 1999), while the fourth image, which only covers a small part of the Region, was made during the following dry season (195/053 acquired February 2, 2000). The rainy season of 1999 was typical of a comparably wet year when the reservoirs were expected to be full, so the satellite images capture the reservoirs' maximum surface areas. The reservoirs were extracted through maximum likelihood classification (Mather, 1999) of the Landsat ETM bands 3, 4 and 5. The visible red and the two infrared bands are well-suited for the detection and delineation of open water bodies. Generally, the spectral reflectance curve of water shows a reduction in reflection with increasing wavelength (Mather, 1999). In bands 4 and 5, the spectral reflectance curve of water is low, whereas the reflectances of soils and healthy vegetation are higher in these bands. This contrast allows us to distinguish between open water and the surrounding land surface. The inclusion of the visible band enhances the contrast between water and soils (Kite and Pietroniro, 2000).

Open surface water is a land cover type that has a wide range of reflectance patterns (Meijering et al., 1994; Kondratyev and Filatov, 1999). This variety is caused by three processes, which are surface reflectance, volume reflectance, and bottom reflectance (Mather, 1999). The scattered component of the surface reflection mainly consists of shorter wavelengths, particularly from the visible part of the spectrum. The infrared part of the spectrum is strongly absorbed. Certain sun-to-sensor constellations and the roughness of the water surface can cause sunglint, while under calm conditions the reflectance may be specular (Mather, 1999; Meijering et al., 1994). The presence of standing or floating vegetation causes a steep ascent in reflectance from the visible to the infrared part of the spectrum, which is characteristic for healthy vegetation (Horler et al., 1983). The signal of the volume reflection is influenced by turbidity, dissolved matter, the trophic status, and algae content of the water. The degree to which the volume reflection contributes to the total reflectance signals of water bodies depends on the penetration depth of light, which decreases from 10 m at 0.5–0.6 μm to less than 10 cm in the range between 0.8 and 1.1 μm (Meijering et al., 1994). The influence of bottom reflectance to the total signal is equally wavelength dependent and mainly originates from the deeper penetrating, shorter wavelengths.

Taking into account the range of reflectance patterns of surface water, the classification was performed with various sub-classes of water, such as clear water, turbid water, water with algae, etc., that were later regrouped again. Freshly burned areas from bushfires and cloud shadows show a spectral overlap with the response patterns of water and are therefore a constraint for remote sensing of open water in the semi-arid tropics (Koutsias et al., 2000). To prevent bushfires and cloud shadows from being misclassified as surface water, these two land cover types were also classified and later discarded (Liebe, 2002). A 3 × 3 median filter was applied to remove single pixels and to fill single-pixel-holes. The remaining river segments were manually deleted. The obtained reservoir map was georeferenced in quadratic mode using 27 reference points, which were taken from 1:50,000 topographic maps. Road intersections were preferred as reference points, but in less developed areas more variable features such as river mouths, and bridges intersecting rivers had to be used, leading to an RMS of 30.2 m.

The classification returned a total of 504 reservoirs with a total acreage of 3408 ha (Table 1). Given the 30 m resolution of the Landsat imagery, the likelihood of incorrectly identifying very small features is high. Three hundred and forty eight reservoirs with acreage of less than 1 ha were therefore deleted from the dataset. The two commercially operated reservoirs, Tono and Vea were also discarded. These are managed by the Irrigation Company Of Upper Region Ltd., ICOUR, which monitors and records the fluctuations of their storage volumes. The remaining 154 reservoirs with a total acreage of 999.54 ha are those herein referred to as small reservoirs, ranging from 1 to 35 ha. Because image acquisition took place in November 1999, and field work from December 2002 to February 2003, there was no direct comparison possible between reservoir outlines as found in the field and in the images. Therefore, the commonly used pixel based user and producer accuracy matrix was not compiled. Instead, an indicator of good user accuracy is the fact that 50% of the areas classified as reservoirs were visited and in each instance a reservoir was indeed found.

A second quality indicator of the classification is given by the comparison of the satellite derived and the ground based surface areas estimates. On average, the field measurements were found to be 13% smaller than the satellite based area estimates, with a standard deviation of 16%. This is not surprising given that field data collection took place later in the dry season. Reservoirs found to be significantly smaller than classified can be explained by intensive irrigation use. The few reservoirs that were found larger than classified showed extensive

Table 1
Results of the satellite based reservoir inventory

Reservoirs	Number	Total surface area (ha)	Percent of total area
All	504	3408	100
Thereof			
Tono	1	1894	56
Vea	1	435	13
"Small"	154	999.54	29
<1 ha	348	79.46	2

areas infested with dense herbaceous water plants in the shallow tail parts of the reservoirs, which were not classified as water due to the dense biomass. The overall correlation of satellite to field measured reservoir surface area has an R^2 of 0.88.

4. Distribution of reservoirs

The distribution of reservoirs pertains both to the statistical distribution of specific properties such as size, and to their distribution over space. Fig. 2 shows the distribution of reservoir sizes. On a semi-log plot, reservoir sizes show a relatively smooth linear distribution. The absence of significant breaks in the distribution is an indicator for the uniformity of the Upper East's topography. Also interesting is the frequency distribution of reservoir sizes. The smallest reservoirs occur at the highest frequency, and with increasing surface area their frequency decreases exponentially (Liebe, 2002). This distribution of reservoir sizes mirrors to some extent general laws in stream morphometry, such as Horton's law of stream numbers (Knighton, 1998). Horton's law refers to the expected number of streams of a certain stream order, where lower order stream segments are more frequent than those of higher orders. In contrast to the stream numbers in Horton's law, however, the reservoirs do not follow a power law distribution (Tarboton et al., 1988).

The spatial distribution of reservoirs and sizes is shown in Fig. 3. It depicts the location of reservoirs in relation to the Upper East's topography, which was compiled from contour lines digitized from 1:50,000 topographic map sheets. The reservoir sizes were categorized, based on a sampling frame that was designed for ground truthing purposes. The total of 154 reservoirs were divided into three approximately equal size groups. Category One has 51 reservoirs of 1–2.79 ha, Category Two has 53 of 2.88 to 6.93 ha, and Category Three has 50 reservoirs of 7.02–35 ha. In Fig. 3, the topography is shown as steps of one standard deviation (35.33 m) from the Region's mean elevation of 197 m (a.s.l.). Most of the reservoirs are located above the mean elevation and yet close to the mean elevation or the fringe area to the next standard deviation step. Conditions favorable for dam construction are indicated by elevation level boundaries that wriggle back and forth, following coves and ledges. Noticeable is the two-sidedness of the elevation distribution with the western half mainly occupying lower elevation ranges, whereas the eastern half lies mainly above the mean elevation. The lower elevations show a lack of reservoirs in comparison to the upper elevations. These lower areas are mainly occupied by the extensive floodplains of the Red Volta, the White Volta, and their tributaries. The occurrence of river blindness used to make the floodplains an unfavorable habitat and they are much less populated than the higher ranges. The higher eastern half of the region has large areas well-suited for settlement and dam construction. Here we find most of the larger reservoirs.

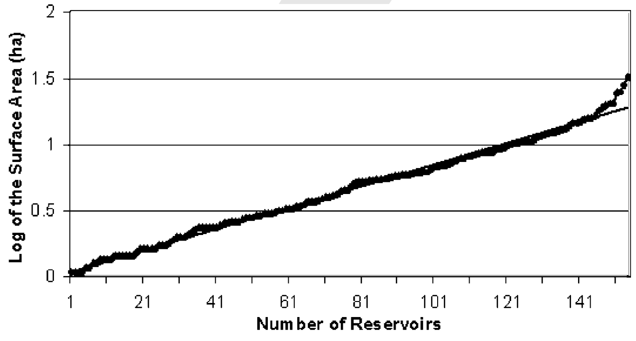

Fig. 2. Reservoir size distribution.

Although drainage pattern and valley shape are important for dam construction, the proximity of a potential dam site to a road is also relevant. Easy access to transportation facilitates construction. Once a reservoir is in use, perishable produce can be brought to market quickly. Morphological regularities can also be deduced from the reservoir distribution. The higher frequency of lower order stream segments also indicates a greater number of potential dam sites and vice-versa. Forest reserves pose a further constraint to dam construction and administrative boundaries also seem to play a role in reservoir distribution (Liebe, 2002). The occurrence of reservoirs can thus be termed "semi-natural", as their existence relies to a great extent on the people's decisions as to where to make use of the available opportunities in the natural landscape.

5. Bathymetrical survey and derivation of area–volume relations

As it is not possible to determine a priori the minimum number of reservoirs to be surveyed to yield a robust area–volume relation, a large sample of almost 40% of the total population was surveyed. This sample contained twenty reservoirs from size Categories One and Three, and 21 reservoirs from Category Two. The outline of each reservoir was mapped using GPS. Bathymetric maps were compiled on the basis of 25–171 GPS-referenced depth measurements, which were taken with a telescopic stadia rod from a boat. In order to get accurate representations of the reservoirs' shapes, care was taken to capture the deepest point, as well as the submerged streambed. This was achieved by oversampling those parts of the reservoirs where the deepest points were expected to be found, taking into account the apparent depth distribution of the in situ measurements. Because a reservoir is a dammed stream, the

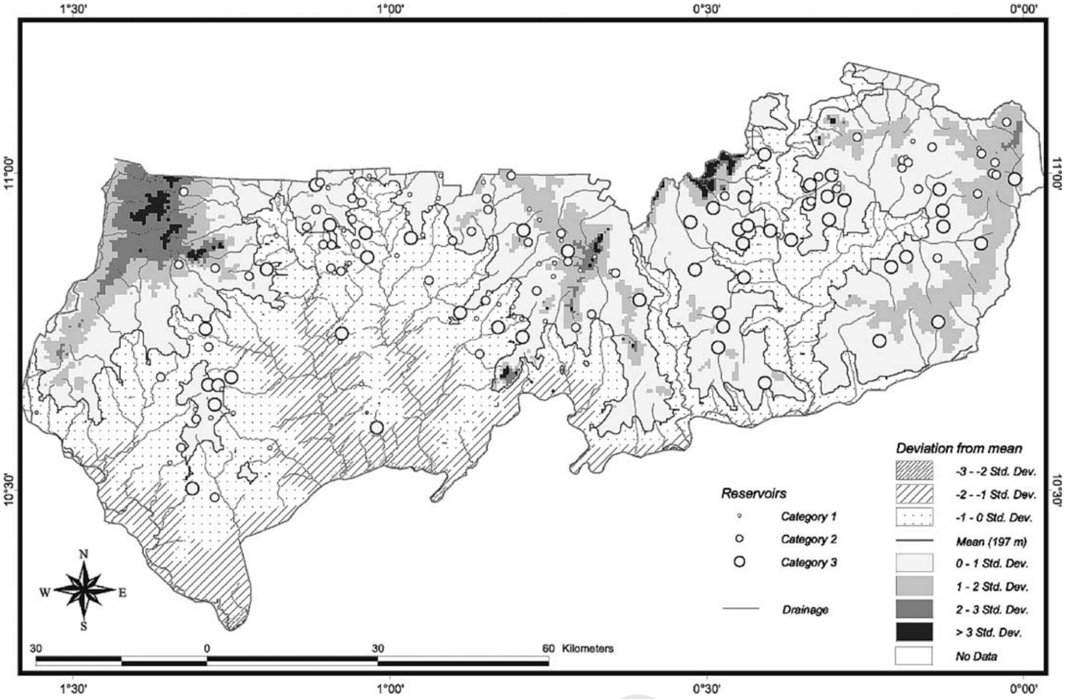

Fig. 3. Distribution of reservoirs with respect to the Upper East Region's topography.

second term of the equation, $1.4367 * \log A$, is close to the expected $3/2 \log A$ in (4). Additional information is contained in the first term of the equation. Comparing (4) and (5) gives

$$-2.067 = \log\frac{1}{6} + \log\frac{1}{f} = -0.778 + \log\frac{1}{f} \tag{6}$$

or

$$f = 19.45. \tag{7}$$

This means that the depth d of a reservoir is ≈1/20 of its characteristic length.

To use Eq. (5) properly for the determination of reservoir volumes, the precision of the prediction needs to be known. The goodness of fit between measured and modeled volumes can be evaluated. The widely used model efficiency measure of Nash and Suttcliffe (1970) indicates that the model explains 97.5% of the measured variance. Despite the variety of reservoir shapes, the derived equations are highly consistent. The sizes of the measured reservoirs are finally summarized in the equation:

$$\text{Volume} = 0.00857 * \text{Area}^{1.4367}\ [\text{m}^3]. \tag{8}$$

Eq. (8) and field measurements show that, at full capacity, the Upper East's 154 small reservoirs can capture up to $185 \times 10^6\ \text{m}^3$ of water.

6. Conclusions and outlook

This research begins to fill the gaps in our knowledge concerning the physical characteristics of small reservoirs as found in the Upper East Region of Ghana. First we established that surface areas of small reservoirs can reliably be mapped on the basis of satellite images. Here, Landsat 7 satellite images were used which in the rainy season may be hindered by clouds. Given the ease with which open water can be mapped with RADAR images (Hess et al., 1995; van de Giesen, 2001), future applications will involve the use of RADAR satellites that are not hindered by clouds and, thereby, allow year-round monitoring of reservoir surfaces.

We also found a relation between reservoir volumes and their surface areas. Eq. (8) relates reservoir areas directly to storage volumes with high precision. Combining Eq. (8) with periodical satellite-based reservoir area measurements would allow us to build a cost effective monitoring system. Such a system is both valuable for hydrological research, as it provides indications of surface runoff in ungauged basins, and for water managers who need estimates of water availability in the Upper East Region of Ghana.

Although their total storage capacity of $185 \times 10^6\ \text{m}^3$ is modest, these reservoirs form a set of well-distributed and easily accessible water sources that can be used for agriculture, domestic use, and livestock. Small dams help to reduce the people's vulnerability to drought and improve their livelihoods. Their modest size minimizes the negative environmental impacts often associated with construction of larger dams. This research will facilitate management of these diffuse systems and ensure their sustainable use.

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