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Key Points:
- A method is presented to approximate area-volume relationships for large reservoirs
- The method makes use of similarity of area-volume relationships within regions
- The method requires only freely available, satellite-based digital elevation models (DEMs)

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Determining water reservoir characteristics with global elevation data

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Abstract Quantification of human impact on water, sediment, and nutrient fluxes at the global scale demands characterization of reservoirs with an accuracy that is presently unavailable. This letter presents a new method, based on virtual dam placement, to make accurate estimations of area-volume relationships of large reservoirs, using solely readily available elevation data. The new method is based on regional similarity of area-volume relationships. The essence of the method is that virtual reservoirs are created in the vicinity of an existing reservoir to derive area-volume relationships for the existing reservoir. The derived area-volume relationships reproduced in situ bathymetric data well. An intercomparison for twelve reservoirs resulted in an average $R^2 = 0.93$. This is a significant improvement on estimates using the best existing global regression model, which gives $R^2 = 0.54$ for the same set of reservoirs.

1. Introduction

Reservoirs have enabled management of water resources for human benefit and have significantly altered the hydrological cycle. Dams have impounded ~ 10,800 km^3 of water since 1900, reducing global sea level by 30 mm and decreasing the rate of sea level rise [*Fiedler and Conrad*, 2015]. Reservoirs have changed seasonal patterns with monthly increases and decreases in streamflow up to 30% [*Haddeland et al.*, 2006]. Delivery of sediments is changed by the presence of reservoirs [*Syvitski et al.*, 2005], as is the bioaquatic connectivity of river systems [*Pringle*, 2001]. As such, characterizing reservoirs globally is of interest to hydrologists, aquatic biologists, river and coastal morphologists, and biogeochemists.

Because of these significant alterations, the impacts of reservoirs should be included in predictions of current and future water availability, floods, and droughts. A new generation of global hydrological models seeks to take the impact of reservoirs into account in contrast to most previous land surface models [*Bierkens et al.*, 2015]. In this context, *Wood et al.* [2011] posed global characterization of reservoirs as a main challenge for the development of global hydrological models. To simulate the effect of reservoirs, depth-storage and area-volume relationships are required but challenging to obtain [*Wood et al.*, 2011]. Area-volume relationships are especially interesting as they allow operational observation of stored volumes by observing areas through satellite remote sensing [*Liebe et al.*, 2009; *Eilander et al.*, 2014]. The dedicated Surface Water and Ocean Topography (SWOT) mission, to be launched in 2020, will improve the temporal and spatial resolution of such observations to the orders of weeks and a few hundred meters [*Biancamaria et al.*, 2016].

The Global Reservoir and Dam (GRanD) Database [*Lehner et al.*, 2011] proposes a globally valid average area-volume relationship based on a regression analysis of bathymetric data of 5824 large reservoirs. This relationship relates the reservoir volume V (10^6 m^3) to area A (km^2) as

$$V = 30.684A^{0.978} \text{ with } R^2 = 0.8 \tag{1}$$

Lehner et al. [2011] reported an R^2 value of 0.8; the application of equation (1) to the set of reservoirs in this study resulted in an average $\widehat{R^2} = 0.54$ (as shown in section 3).

Regional, rather than global, area-volume relationships are likely to give better results because geomorphological similarity is expected. Previous research on small reservoirs shows that regional derivation of area-volume relationships gives accurate results. *Liebe et al.* [2005]; *Annor et al.* [2009]; *Sawunyama et al.* [2006]; *Rodrigues et al.* [2010] derived area-volume relationships for small reservoirs in basins in Ghana, Brazil, and Zimbabwe from bathymetry. They found that the area-volume relationships could be described with power relationships similar to equation (1) but that the coefficient and exponent varied among basins. These regional area-volume relationships for small reservoirs had a coefficient of determination R^2 ranging from 0.89 to 0.98, significantly higher than the GRanD relationship. The exponent ranged between 1.2 and 1.5, close to the 1.5 that follows from geometrical considerations [*Liebe et al*., 2009]. Actually, the exponent in equation (1) is difficult to interpret as it is unclear what shape a valley has to have to produce an exponent of less than one.

The results of earlier studies [*Liebe et al*., 2005; *Annor et al*., 2009; *Sawunyama et al*., 2006; *Rodrigues et al*., 2010] on small reservoirs suggest that there is a power law relationship between area and volume within a geomorphologically homogeneous region. One could see these relationships as a geomorphological measure, comparable to Horton-Strahler ratios, the Cumulative Area Distribution, or the Hypsometrics Relation [*Rodríguez-Iturbe et al*., 1992; *Langbein*, 1947]. The more homogeneous an area is from a geomorphological point of view, the better one would expect these relationships to hold over that area. For this application, we are looking at topography within an area near an existing reservoir. Topography is the result of long-term processes ($>$1 Ma). Time, tectonics, geology, and climate are the main geomorphological determinants at this time scale [*Schumm and Lichty*, 1965]. So if a complete mountainous area has been formed from a geologically homogeneous substratum (lithology, structure) that was uplifted synchronously, one would expect good results. When a geologically heterogeneous substratum was uplifted in parts at different points in time or at different paces, the expected results would be worse.

Given that we can derive regional area-volume power relationships for small reservoirs, one may hypothesize that this is also possible for large reservoirs. In this study, we test this hypothesis and examine whether it is indeed possible to estimate the area-volume relationships for large reservoirs with similar accuracies as those found for small reservoirs. A new method, using virtual reservoirs, is used for the derivation of area-volume relationships. The method is based on the analysis of area-volume properties of nearby potential reservoir locations. Two dam placement methods are examined, placement of virtual dams in the same valley and placement of virtual dams in neighboring valleys. The new method opens the way for global mapping of reservoir characteristics on the basis of readily available global elevation data.

2. Materials and Methods

2.1. Materials

Topographical analysis is based on the digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) [*U.S. Geological Survey*, 2014]. Areas between 60° north and 56° south have been mapped by the SRTM in February 2000. The spatial resolution of the SRTM is 1 arc sec by 1 arc sec, approximately equal to 30 × 30 m, between latitudes 50° north and 50° south. Tiles outside this range have a resolution of 2 arc sec by 1 arc sec. The linear vertical absolute accuracy is better than 16 m; linear relative height accuracy is better than 10 m. Circular absolute and relative height accuracy are respectively 20 and 15 m. These accuracies follow a 90% confidence level. [*Farr et al*., 2007].

For validation, bathymetric data of the reservoirs listed in Table 1 were used. These reservoirs were selected based on their diverse geomorphological locations and the availability of *in situ* bathymetric data. Such in situ data were not readily available and were the most limiting factor for more exhaustive method validation. The area-volume relationship derived from the GRanD Database (equation (1)) was used to indicate the improvement of remote sensing estimation of reservoir volumes proposed in this paper.

Data preparation was performed using Quantum Geographic Information System [*QGIS 2.6.1*, 2014]. Area-volume relationships were derived using the Geographic Resources Analysis Support System [*GRASS 7.0.0*, 2014] Geographic Information System (GIS). Python 2.7.3 scripts were used to automate the procedure. These scripts are available at 10.5281/zenodo.51388.

2.2. Methods

To determine the area-volume relationships for large reservoirs, a method with virtual dams was developed. In the DEM, five dams were placed in the surroundings of the existing dam. Two approaches for virtual dam placement were used in this study. One approach was virtual dam placement in the same valley, upstream and downstream of the existing reservoir. The other approach was virtual dam placement in surrounding valleys, located in the same geomorphological region. The dams were placed at locations that looked similar in terms of valley widths and slope by visual inspection. The area of the virtual dam could not overlap with the part of the existing reservoir that was covered by water during the Shuttle mission. Such areas appear flat and

Table 1. Reservoirs With Their Corresponding Attributes Used in This Study. Storage Capacity Was Obtained From the Reservoir Studies Indicated in the Reference Column

Reservoir Name	Country	Latitude/Longitude	Storage Capacity (km^3)	Year of Completion	Year of Bathymetric Survey	Reference
Cerro Prieto	Mexico	32°24′36.0″N/115°19′36.1″W	0.39	1982	1993	*Yutsis et al.* [2014]
Fort Cobb	USA	35°11′11.4″N/98°28′17.3″W	0.35	1950	1993	*Ferrari* [1994]
Fresno	USA	48°39′24.2″N/109°58′46.7″W	0.24	1939	1999	*Ferrari* [2000]
Gibson	USA	47°36′32.2″N/112°47′45.1″W	0.13	1929	1996	*Ferrari* [1996]
Hirakud	India	21°32′11.8″N 83°51′44.1″E	8.1	1957	2012	*Tobgay* [2014]
John Redmond	USA	38°14′44.5″N/95°47′48.1″W	0.11	1959	2014	Kansas Biological [2010]
Kirwin	USA	39°39′37.2″N/99°08′24.8″W	0.39	1955	1996	*Ferrari* [1997]
Manso	Brazil	14°52′32.6″S/55°46′20.7″W	4.0	1999	Unkown	*Carvalho and Lou* [1990]
Roseires	Sudan	11°43′37.3″N/34°23′38.0″E	0.33	1966	1966	*Ali et al.* [2013]
Saidenbach	Germany	50°44′04.1″N/13°14′02.1″E	0.022	1933	1995	*Baumert et al.* [2005]
Singur	India	17°48′05.4″N/77°54′28.1″E	0.72	1998	2005	*Jeyakanthan and Sanjeevi* [2011]
Triadelphia	USA	39°12′28.9″N/77°00′53.8″W	0.020	1943	2004	*Ortt et al.* [2007]

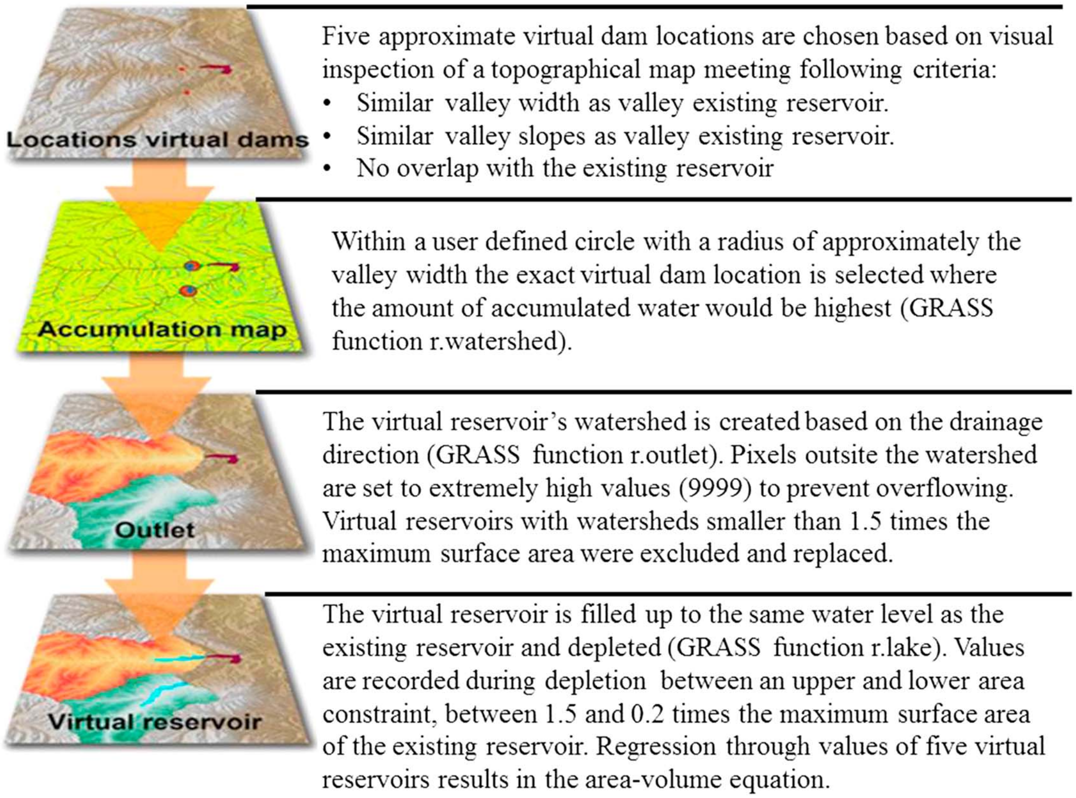
do not contain the bathymetric information needed to derive area-volume relationships. The script user selected an approximate dam location and a search area for the exact dam location by drawing a circle with a radius of approximately the valley width. The Python script then automatically found the exact virtual dam location within this circle, defined as the maximum accumulation point in this user-defined circle.

For each virtual dam, the watershed was determined. Virtual reservoirs with a maximum area smaller than 1.5 times the maximum area of the actual reservoir were excluded and replaced by another virtual reservoir that did meet this upper area constraint. In order to bracket the volume-area relationship of the actual reservoir we filled the five virtual reservoirs to an area of maximally 1.5 times the area of the existing reservoir and emptied the virtual reservoirs in steps of one meter to an area of 0.2 times the existing reservoir. The choices for 1.5 and 0.2 were somewhat arbitrary but considered reasonable and sufficient to cover the range of volumes of interest. A simple sensitivity analysis was performed to determine the effect of lowering the maximum extent to 1.2 times the existing reservoir. A power relationship was fitted through the points obtained for five reservoirs for all levels meeting these area constraints to obtain the area-volume relationship. A graphical description of the area-volume relationship derivation including the GRASS functions used is given in Figure 1.

For all investigated reservoirs it was possible to find five similar locations with nonoverlapping surface areas larger than 1.5 times the maximum surface area of the existing reservoir. Finding more suitable locations was difficult especially in areas that looked more heterogeneous. An initial sensitivity analysis on the number of reservoirs needed to establish a robust area-volume relationship showed that in most cases three reservoirs were sufficient and that more than five reservoirs led to worse results, particularly in heterogeneous regions where the number of virtual reservoir locations meeting the criteria in Figure 1 was small.

The five locations of virtual dams were specified by the user based on the criteria listed in Figure 1. To test the sensitivity of the results to this user-defined input, thirteen different people were asked to identify suitable virtual reservoir locations for the reservoirs Fort Cobb and Kirwin and estimated area-volume relationships were compared.

It would be preferable to have a simple objective measure for similarity rather than a somewhat subjective human judgment. Different objective measures were determined to examine if these could predict the goodness of fit between the virtual area-volume relationship and the actual area-volume relationship. We also examined if these measures predicted whether same or different valley placement of the virtual reservoirs produced better results. The measures were the Horton-Strahler number of the different river branches in which the virtual dams were placed, the range of the coefficients of determination of the area-volume relationships of individual virtual reservoirs, and the range of coefficients in the power relationships between area and volume for the individual virtual reservoirs. The Horton-Strahler number was chosen because it is a very commonly used geomorphological parameter for the order of a stream. Headwaters are first-order streams with a Horton-Strahler number of one. When two streams come together, they form a second-order stream with a Horton-Strahler number of two; when two second-order streams come together, they form a



Five approximate virtual dam locations are chosen based on visual inspection of a topographical map meeting following criteria:

- Similar valley width as valley existing reservoir.
- Similar valley slopes as valley existing reservoir.
- No overlap with the existing reservoir

Within a user defined circle with a radius of approximately the valley width the exact virtual dam location is selected where the amount of accumulated water would be highest (GRASS function r.watershed).

The virtual reservoir's watershed is created based on the drainage direction (GRASS function r.outlet). Pixels outsite the watershed are set to extremely high values (9999) to prevent overflowing. Virtual reservoirs with watersheds smaller than 1.5 times the maximum surface area were excluded and replaced.

The virtual reservoir is filled up to the same water level as the existing reservoir and depleted (GRASS function r.lake). Values are recorded during depletion between an upper and lower area constraint, between 1.5 and 0.2 times the maximum surface area of the existing reservoir. Regression through values of five virtual reservoirs results in the area-volume equation.

Figure 1. Description of the steps in the procedure to obtain storage area relationships including GRASS functions used. Python was used to automate the steps.

third order stream; and so on. The other two measures were chosen because one would expect large ranges if the area is inhomogeneous with respect to area-volume relationships. In order to make meaningful comparisons between the coefficients in the power relationships, the exponents in these relationships needed to be fixed; otherwise, a larger exponent could compensate for a smaller coefficient. For this reason, we fixed the exponents at 1.5, in which case the coefficient would be a perfect measure of valley width and slope for triangular valley profiles.

3. Results

Area-volume relationships for 12 reservoirs were obtained using the method of virtual dams (see Table 2). The equations were determined for dam placements in the same valley and in different valleys. As can be seen in Table 2, the obtained equations had an exponent in the range of 1.29 and 1.91. The fit through the area-volume points obtained with the virtual dams was good (see Table 2 for coefficient of determination, R_A^2(Fit) > 0.69, average R_A^2(Fit) = 0.92), indicating regional similarity. (Validation of the equations was done by calculating the coefficient of determination between the obtained equation and the bathymetry data for each reservoir (see Table 2 column R_A^2(Fit-Bat)). Highest and lowest correlation between the newly proposed method and bathymetric surveys were found for Saidenbach (R_A^2(Fit-Bat) = 0.98 based on area-volume correlation from virtual reservoirs in the same valley as the Saidenbach reservoir) and Singur (R_A^2(Fit-Bat)=0.69 based on area-volume correlation obtained from virtual reservoirs in valleys adjacent to the Singur reservoir) reservoirs, respectively.

Differences between the two placement methods were observed. For example, derivation of the area-volume relationship for the Gibson reservoir resulted in a higher correlation with bathymetry data for same valley placement (R_A^2(Fit-Bat) = 0.92) than for different valley placement (R_A^2(Fit-Bat) = 0.79). Derivation for the area-volume relationship for Fort Cobb resulted in a higher correlation with bathymetry data for different valley placement (R_A^2(Fit-Bat) = 0.96) than for same valley placement (R_A^2(Fit-Bat) = 0.86). On average, same valley placements (average R_A^2(Fit-Bat) = 0.93) led to better results than different valley

Table 2. Results After Applying the Method of Virtual Dams[a]

Reservoir Name	Placement	Equation A	R_A^2(Fit)	R_A^2(Fit-Bat)	Equation B	R_B^2(Fit)	R_B^2(Fit-Bat)	R^2(GRanD-Bat)
Cerro Prieto	Same	$V(A) = 0.0044 \times (A)^{1.4473}$	0.98	**0.98**	$V(A) = 0.001849 \times (A)^{1.5}$	0.97	**0.99**	0.27
	Different	$V(A) = 0.0026 \times (A)^{1.510}$	0.77	0.75	$V(A) = 0.003066 \times (A)^{1.5}$	0.77	0.75	
Fort Cobb	Same	$V(A) = 0.0135 \times (A)^{1.4018}$	0.95	0.86	$V(A) = 0.002602 \times (A)^{1.5}$	0.95	0.84	0.55
	Different	$V(A) = 0.0005 \times (A)^{1.5697}$	0.93	**0.96**	$V(A) = 0.001630 \times (A)^{1.5}$	0.93	**0.97**	
Fresno	Same	$V(A) = 1.3712 \times 10^{-6} \times (A)^{1.910}$	0.97	**0.94**	$V(A) = 0.001412 \times (A)^{1.5}$	0.93	**0.97**	0.47
	Different	$V(A) = 0.0400 \times (A)^{1.3243}$	0.91	0.90	$V(A) = 0.002138 \times (A)^{1.5}$	0.90	0.88	
Gibson	Same	$V(A) = 0.0091 \times (A)^{1.4838}$	0.84	**0.92**	$V(A) = 0.007127 \times (A)^{1.5}$	0.84	**0.92**	0.87
	Different	$V(A) = 0.0025 \times (A)^{1.6282}$	0.95	0.79	$V(A) = 0.016644 \times (A)^{1.5}$	0.94	0.81	
Hirakud	Same	$V(A) = 0.0211 \times (A)^{1.2997}$	0.94	**0.98**	$V(A) = 0.000408 \times (A)^{1.5}$	0.92	**0.98**	0.65
	Different	$V(A) = 0.0017 \times (A)^{1.4476}$	0.97	0.93	$V(A) = 0.000587 \times (A)^{1.5}$	0.97	0.93	
John Redmond	Same	$V(A) = 0.0022 \times (A)^{1.4365}$	0.91	0.82	$V(A) = 0.000763 \times (A)^{1.5}$	0.91	0.81	0.27
	Different	$V(A) = 0.0246 \times (A)^{1.2890}$	0.95	**0.87**	$V(A) = 0.000704 \times (A)^{1.5}$	0.93	**0.84**	
Kirwin	Same	$V(A) = 0.0026 \times (A)^{1.4804}$	0.95	0.93	$V(A) = 0.001884 \times (A)^{1.5}$	0.95	0.93	0.55
	Different	$V(A) = 0.0011 \times (A)^{1.5043}$	0.99	**0.97**	$V(A) = 0.001255 \times (A)^{1.5}$	0.99	**0.97**	
Manso	Same	$V(A) = 0.0018 \times (A)^{1.4917}$	0.88	**0.91**	$V(A) = 0.001533 \times (A)^{1.5}$	0.88	**0.92**	0.88
	Different	$V(A) = 0.0040 \times (A)^{1.455}$	0.86	0.88	$V(A) = 0.001726 \times (A)^{1.5}$	0.86	0.88	
Roseires	Same	$V(A) = 0.0039 \times (A)^{1.4247}$	0.87	**0.92**	$V(A) = 0.000963 \times (A)^{1.5}$	0.87	**0.90**	0.54
	Different	$V(A) = 0.0018 \times (A)^{1.4699}$	0.90	0.86	$V(A) = 0.001047 \times (A)^{1.5}$	0.90	0.86	
Saidenbach	Same	$V(A) = 0.0506 \times (A)^{1.3951}$	0.98	**0.98**	$V(A) = 0.012083 \times (A)^{1.5}$	0.98	**0.98**	0.59
	Different	$V(A) = 0.0145 \times (A)^{1.4718}$	0.95	0.93	$V(A) = 0.009880 \times (A)^{1.5}$	0.95	0.94	
Singur	Same	$V(A) = 0.0090 \times (A)^{1.3511}$	0.93	**0.97**	$V(A) = 0.000618 \times (A)^{1.5}$	0.92	**0.95**	0.48
	Different	$V(A) = 0.0053 \times (A)^{1.4236}$	0.93	0.69	$V(A) = 0.001341 \times (A)^{1.5}$	0.93	0.68	
Triadelphia	Same	$V(A) = 0.0139 \times (A)^{1.4242}$	0.98	**0.95**	$V(A) = 0.004703 \times (A)^{1.5}$	0.97	**0.94**	0.33
	Different	$V(A) = 0.0157 \times (A)^{1.4283}$	0.95	0.89	$V(A) = 0.005647 \times (A)^{1.5}$	0.95	0.87	
Average	Same		0.93	0.93		0.92	0.93	0.54
	Different		0.92	0.87		0.91	0.86	
Overall average			0.92	0.90		0.92	0.90	0.54

[a] Third and sixth columns show the area-volume relationship obtained from regression trough the points from the five virtual reservoirs for *Same* and *Different* valley placement for varying exponent (*Equation A*) and fixed exponent (*Equation B*). Fourth and seventh columns show the corresponding coefficient of determination. Fifth and eighth column show the coefficient of determination of the equations with bathymetry data. Ninth column shows the coefficient of determination of the GRanD equation (1) and bathymetry data. The best fit of R^2(Fit-Bat) Same, R^2(Fit-Bat) Different, and R^2(GRanD-Bat) per reservoir for varying and fixed exponents are given in bold.

placement (R_A^2 (Fit-Bat) = 0.87). More importantly, same valley placement always produced good results (R_A^2 (Fit-Bat) > 0.8), while different valley placement led to some poor results (R_A^2(Fit-Bat) = 0.69).

The sensitivity with respect to the maximum extent of the virtual reservoir was very small. For the same valley placements, average R^2(Fit-Bat) = 0.926 when points up 1.5 times the maximum area were taken into account, while R^2(Fit-Bat) = 0.924 with points up 1.2 times the maximum area. This implies that smaller surfaces can be used when same valley placements with 1.5 times the actual reservoir size are absent.

For all reservoirs the best fit obtained with either the same valley or the different valley approach was better than the fit obtained with the GRanD equation (equation (1)). The same valley placement method performed much better than the GRaND equation, as shown in Figure 2. This figure compares for each reservoir the volumes corresponding to six equal area-spaced points from the bathymetric survey to the volumes estimated with the presented method and the GRaND equation. The GRaND reservoir showed a clear overestimation of the reservoir volumes except for the Gibson and Manso reservoirs. The same valley method also overestimated reservoir volumes but much less than the GRaND equation. The scatterplot of the new method was closer to the expected straight 1:1 line and has a R^2 values of 0.81, calculated over the points displayed in Figure 2, which is a subset of data used for Table 2, in contrast to the $R^2 = 0.30$ found for the GRaND equation.

The effect of the user defined input of the approximate virtual reservoir location on the area-volume relationships was evaluated for Fort Cobb and Kirwin. Thirteen different users were asked to identify suitable virtual reservoir locations following the criteria listed in Figure 1. Following the criteria, they found it easy to identify suitable locations, often choosing the same or nearby locations. The implicit definition of what a user considers similar varied among existing reservoir locations. Where many potential locations were available, the range of valley widths and slopes varied only ±20%, whereas at the sites with few suitable locations, the

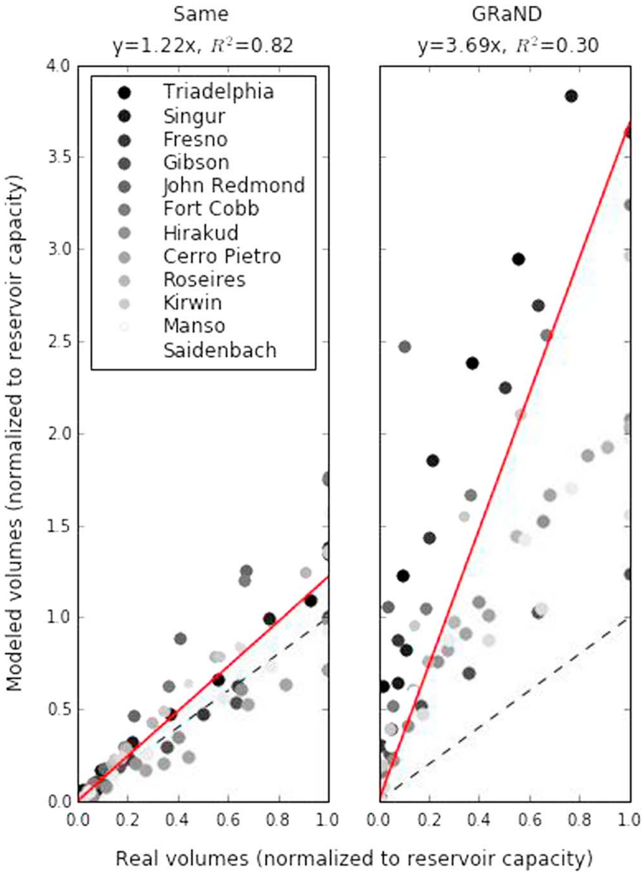


Figure 2. Scatterplot of all real volumes against modeled volumes for (left) same valley placement and the (right) GRaND approximation. For each reservoir the real volumes corresponding to six equally area-spaced points from the bathymetric data are plotted against the volumes obtained from area-volume relationships for the same six points. The volumes are normalized by the maximum volume of the actual reservoirs. Linear regression equations and coefficients of determination are shown above the plots. The dashed black one:one line indicates a perfect fit between calculated and measured volumes.

range in widths and slopes reached ±50%. In those cases, in which different locations were chosen, still similar area-volume relationships were found. For the two reservoirs, all area-volume relationships identified by the different users correlated with the bathymetric data with $R^2 > 0.9$. The average exponents for Fort Cobb and Kirwin were respectively 1.48 and 1.43 with standard deviations of respectively 0.03 and 0.05. The spread of the lines was quite constant over all points in the area-volume relationships. For Fort Cobb, the ratio of the volume standard deviation over the volume mean was on average 0.16 with a standard deviation of 0.002. For Kirwin this ratio was on average 0.12 with a standard deviation of 0.02.

None of the three homogeneity measures (Horton Strahler, variation in coefficients of determination, and variation in coefficients) showed any predictive power, neither with respect to the goodness of fit of the predicted bathymetry nor whether "same" or "different" valley placement would produce better results. The coefficients and exponents in the power relationship between area and volume giving the best fits for individual virtual reservoirs were interdependent. Very similar fits were obtained by decreasing/increasing the coefficient while increasing/decreasing the exponent. This implied that the difference in exponents or coefficients for different virtual reservoirs were not a good measure of homogeneity. Instead, we fixed the exponent at 1.5 and fitted the best coefficient. Interestingly, as Table 2 shows, the bathymetry fit was still very good when a fixed exponent of 1.5 was used.

4. Discussion

The new method proposed in this paper provides a good estimation of reservoir area-volume relationships based on globally available elevation data. These relationships can improve global hydrological models and water management in general as they provide a solution to lack of available reservoir data. The method provides a significantly better estimation than the GRanD estimation. On average, the new method overestimates storage by 20%, whereas the GRanD equation overestimates storage by 370%. Total storage in these reservoirs was 15 billion m^3, so for these particular reservoirs, overestimations were 3 billion m^3 for the new method and 55 billion m^3 for the GRanD equation. Regional geomorphological characteristics, such as slopes, appear to be a better predictor for area-volume relationships than global average relationships of existing reservoirs. This is in line with previous research on small reservoirs [*Liebe et al.*, 2005; *Annor et al.*, 2009; *Sawunyama et al.*, 2006; *Rodrigues et al.*, 2010]. Relief does not influence the accuracy of the presented method. For both very flat regions (e.g., Cerro Prieto) and for regions with extreme relief (e.g., Gibson) good estimations of the area-volume relationship are derived. Overestimation of the volumes may be explained by reservoir sedimentation. Due to sedimentation, the storage of a reservoir can be reduced significantly after several years [*Mahmood*, 1987] and most bathymetric data were collected several years after the dam was constructed (see Table 1).

As was to be expected, the success of the method does depend on the geomorphological homogeneity of the environment of the reservoirs. Closer examination of the DEMs showed that different valley placement was more accurate in homogeneous areas and same valley placement in heterogeneous areas. For example, the environment of Fort Cobb is formed by the geologically homogeneous Rush Springs Formation, dominated by Permian sandstone (http://mrdata.usgs.gov/geology/state/map.html?x=-98.460587&y=35.171942&z=10#). In contrast, the environment of the Gibson reservoir crosses several fault lines and is situated in a geologically heterogeneous area with Gabbro, Diorite, Limestone, Glacial Drift, and mixed clastic rock, of Jurassic, Devonian, and Mississippian origin (http://mrdata.usgs.gov/geology/state/map.html?x=-112.793676&y=47.602081&z=12#). Geomorphological homogeneity is not a simple concept, given the hierarchical nature of units and the interaction between spatial and temporal scales [*De Boer*, 1992]. It is beyond the scope of this study to go much further than this general idea, but it should be assumed that the proposed method will provide better results in geologically homogeneous areas.

None of the three homogeneity measures chosen were predictors of the final goodness of fit or of whether the same or different valley method produced better results. Neither the Horton-Strahler ratio nor the range of coefficients of determination of the area-volume relationships of individual virtual reservoirs showed any correlation with the goodness of fit with the bathymetric data. Remarkably, fixing the exponent at 1.5 hardly affected the overall results (Table 2). This allowed us to use variation of the coefficients with fixed exponent as a measure of homogeneity. The advantage would have been that this coefficient is a very direct measure of valley width and slope. Unfortunately, the variation of coefficient values of individual virtual reservoirs also had no predictive value for the final goodness of fit with bathymetry, nor did the variation predict whether the same or different valley method produced the best results.

In this study, five locations of virtual dams were used to derive the area-volume relationships and locations were specified by the user for each of the two approaches. The sensitivity of the results to the user defined input of the approximate reservoir location was small. A logical next step would be to automate reservoir location identification using pattern recognition algorithms or, alternatively, use a citizen science approach similarly to the Cyclone project (http://www.cyclonecenter.org) or microtasking [*Larson et al.*, 2014]. Such an approach would also allow us to quantify more specifically what users consider similar valley locations in terms of spread in valley slope and valley width.

The presented approach can be used to provide surface areas and volumes urgently needed for global hydrological models [*Wood et al.*, 2011] and can be extended to infer actual operational rules based on solely space borne remote sensing. With area-volume relationships available, any space-born measurement of surface area or altimetry can be used to estimate reservoir water storage as shown, for example, by *Gao et al.* [2012]. Hydrological models can be used to predict the inflow, and outflow could be derived from the reservoir water balance. Such an approach would enable the evaluation of the accuracy of current reservoir models [e.g., *Haddeland et al.* [2006]] and, more importantly, the evaluation of reservoir operation efficiency at a global scale.

5. Conclusion

This letter presented a new method to derive area-volume relationships for large reservoirs solely using readily available global elevation data. The new method was based on the regional similarity of area-volume relationships. The method used virtual reservoirs created in the vicinity of an existing reservoir to derive the area-volume relationship. Around an existing reservoir, five approximate locations for virtual reservoirs were selected according to three simple criteria. The exact dam location was then determined through an automated optimization algorithm. Finally, a power relationship was fitted through the aggregated area-volume plot. The fitted area-volume relationships were compared with bathymetric data from twelve reservoirs.

Two variations of the method were tested. First, virtual reservoirs were placed in the same valley. Second, virtual reservoirs were placed in valleys around the existing reservoir. The same valley method always produced good results and was, therefore, preferable. Both variations significantly outperformed the global regression equation derived from the GRanD database. The new method predicted measured bathymetry with an average coefficient of determination $R^2 = 0.93$, which is significantly better than the GRanD regression equation, which has an average $R^2 = 0.54$ for the same reservoirs. The method opens the way to accurate reservoir characterization at global scale.

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