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Original Research Article

Calculation of reservoir capacity loss due to sediment deposition in the `Muela reservoir, Northern Lesotho

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A B S T R A C T

Bathymetry survey records of the `Muela Reservoir in northern Lesotho were obtained from the Lesotho Highlands Development Authority (LHDA) with the aim of identifying reservoir storage capacity loss due to sediment deposition, between 1985 and 2015. For this purpose, data from eight surveys completed between 1985 and January 2015 were analyzed to quantify bathymetric change between each survey. Four interpolation methods (inverse distance weighting, Kriging, natural neighbor, and spline), were used to create digital terrain models from each survey data-set. In addition, a triangulated irregular network (TIN) surface was created from each data-set. The average reservoir storage capacity loss of 15,400 m^3/year was determined across the whole period between 1985 and early 2015, based on Kriging. Whilst the results indicate high inter-annual variability in the rate of reservoir capacity reduction, consideration of errors in the surveying and reservoir volumetric calculation methods suggest that rates of reservoir volume reduction can vary between 11,400 m^3/year and 18,200 m^3/year.

1. Introduction

Lesotho (also known as the water tower of Africa) is a country for which water is one of its greatest assets; unfortunately it has also come to be known as a country with one of the highest rates of soil erosion in the world (Showers, 2005), and the associated high rates of loss of reservoirs storage capacities due to sediment deposition (Chakela, 1981). Despite this dichotomy, the government of Lesotho is making good of the water resource potential of the country by entering a joint venture with South Africa to exploit both the water resource and hydro-electric power potential of its highland areas. The ongoing problem of reservoir sedimentation however, will require careful monitoring if related projects are to reach their full potential. This study presents recent and historic bathymetric data from the `Muela Reservoir in NW Lesotho and assesses the usefulness of such data for estimating historic and contemporary rates of sedimentation. The extent and uncertainty of this problem, and the implications for other such reservoirs within the region, are then discussed.

Use of GIS tools in calculating reservoir bathymetry has long history. For example, calculation of reservoir storage capacity loss due to sediment deposition (using echo-sounding data), have been performed in the US Triadelphia reservoir since 1942 (Ortt, Van-Ryswick, & Wells, 2007). A GIS-based study was also carried out in Ohio, for assessment of the impact of removal of the Ballville Dam across the Sandusky River (Evans, Levine, Roberts, Gottgens, & Newman, 2002). In 2004, the Canadian Ministry of Natural Resources Ontario compiled a detailed manual for performing bathymetric survey using GPS integrated echo-sounders, and how to transfer the survey data to ArcGIS software for fast and easy bathymetry computation (Levec & Skinner, 2004). In 2010, Alcântara et al., used a CAD software to extract historical contours from topographic maps and integrate it with an SRTM data to derive the bathymetry of a tropical reservoir (Alcântara et al., 2010).

Despite the above developments, analyses of sounding data in GIS to obtain reservoir storage capacity are barely covered in existing literature. Consequently, GIS have been rarely been used for this purpose in Lesotho. In Lesotho, most Government Departments, parastatals and private sector bodies use GIS in their day-to-day operations. The Lesotho Highlands Development Authority (LHDA), which is in charge of operation and maintenance of the reservoirs of the Lesotho Highlands Project, often engage international consultants to handle and analyze the annual sounding data of inundated reservoirs for the purpose of monitoring their storage capacity losses. Such methods involve crude cut-and-fill survey and calculation techniques that are commonly used in

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construction sectors, but involved linear interpolation of the surveyed data.

In this study, the objective was to use a series of annual survey data from the LHDA, to assess applicability of the different geospatial interpolation techniques to calculate the loss of storage capacity of the `Muela Reservoir in Northern Lesotho. This study aims to determine the most efficient and robust interpolation techniques for use in reservoir volume estimation in data-sparse environments such as the semi-arid Southern African region.

2. The study area

The `Muela Resrvoir is situated in the Nqoe River catchment in the Northern Lesotho, and is part of the Lesotho Highland Water Project that is co-owned by the Kingdom of Lesotho and the Republic of South Africa.

2.1. Lesotho Highlands Water Project

The Lesotho Highlands Water Project (LHWP) is a multi-phased project designed to deliver water to the industrial and economic hub of the Gauteng region of South Africa, and generate hydro-electric power for Lesotho. Phase I of the project was completed in 2003 with the completion of the Katse Reservoir (Fig. 1) and associated infrastructure (including a water-transfer tunnel to the Muela Hydro-Power station); and the Muela Dam and delivery tunnel to the Ash River outfall in South Africa. The nominal annual yield of the project at that stage was 780 million m^3/year. Phase II of the project will not be completed until 2020, and will increase the supply rate to 1255 million m^3/year. The hydro-power capacity of the scheme will also be increased from 72 MW, with the addition of a 1200 MW pumped water storage scheme (LHDA, 2014). The quantification of rates of sedimentation in Lesotho's highland reservoirs is therefore, of increasing importance to successful delivery, and subsequent management of the project.

2.1.1. `Muela Reservoir

Construction of the 6 million m^3 capacity, `Muela reservoir in Northern Lesotho started in 1994 and was completed in 1997 (Arthur, Wagner, & Hein, 1997; Jacobs, 2011). The purpose of the reservoir was to store water from the `Muela Hydropower Plant, prior to its transfer to the Ash River (Bailey, 2013; DWAF, 2014; Wallis, 1992). The reservoir is situated within the north westerly draining Nqoe River catchment (27 km^2), (Fig. 1). The altitude at the base or reservoir dam wall is 1730 m amsl, whilst the upper parts of the catchment increase to 2230 m (latitude: 28.73°S to 28.85°S; longitude: 28.43°E and 28.52°E). A meteorological station at St. Peters Mission which lies just northeast and adjacent to the Nqoe catchment has rainfall data for the twelve years between 1990 and 2004, with three years of missing record from 1994 to 1996. A second station at the `Muela hydropower plant (Lesotho Highlands Development Authority (LHDA)), has rainfall data for the period 2005–2014. The rainfall data from the St. Peters station indicate a mean annual rainfall of 810 mm, with annual rainfall ranging from 544 mm to 1069 mm between 1990 and 2014 (Fig. 2).

The dominant geology of the catchment is basalt of the Lesotho formation which forms the upper reaches of the catchment (Fig. 3). Massive fine-grained sandstones of the Clarens formation (Bailey, 2013), predominate in the lower catchment and at the location of the `Muela Dam (Panagos, Jones, Bosco, & Senthil, 2011; Wallis, 1992).

The Lesotho soil association map (Land & Soil Conservation Department, 2014), categorizes the soils of the catchment as Fersiallitic soils (coarse silt-loam); Lithosols on Ferro magnesium / sedimentary rocks (gravelly silt loam); Lithosols on lava (very coarse gravelly silt loam); Lithosols on lava / calcimorphic soils (coarse gravelly silt loam); and Vertisols / calcimorphic soils (medium silt loam) (Fig. 4). The distribution of different land-use / cover types within the catchment, derived from satellite imagery via Google-Earth, is also shown in Fig. 4. Land use / cover types were visually identified on Google-Earth satelite images. Still in Google-Earth, a polygon boundary was drawn using visual assessment to enclose each land-use / cover type and then stored in

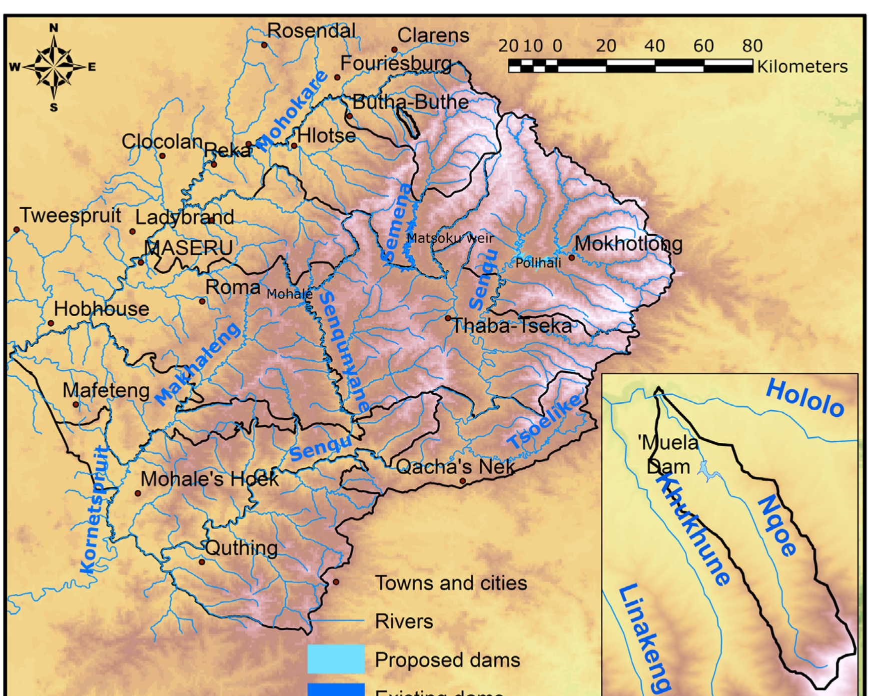

Fig. 1. Location of the Nqoe Catchment relative to existing and proposed dams of the Lesotho Highlands Water Project.

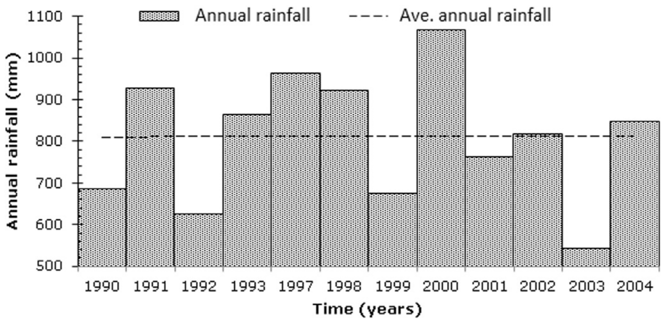

Fig. 2. Annual rainfall for the Nqoe Catchment (St Peters Mission) from 1990 to 2004.

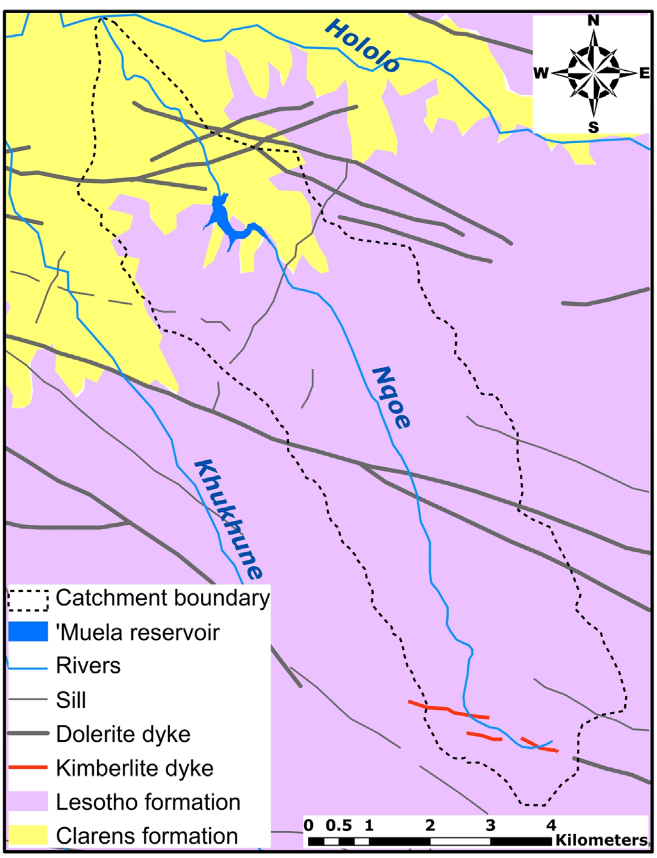

Fig. 3. Geology map of the area around the Nqoe River catchment.
Source: Ministry of Mines and Geology (1982), Department of Water Affairs, and Land Use Planning Lesotho

different folders created in Google-Earth. Each folder contains polygons of the same land-use / cover. Each of these land-use / cover folders were saved as kmz file types which were then imported into ArcMap10x to create shapefiles for the land-use / cover maps. In Fig. 4, it can be seen that the dominant land-use / cover in the catchment is 'grassland' (communal rangelands), which is found predominantly on steeper slopes and in areas of high relief. 'Croplands' dominate areas of lower slope and low relief, even though some are still on very steep slope and high relief as depicted in Plate 1.

The LHWP treaty, signed by the South African government and the Kingdom of Lesotho in 1986, requires the LHDA to release a mean annual outflow of 5.05 million m^3 from the `Muela reservoir into the Nqoe River (LHDA, 2003; Matete, 2004). Until November 2004, water was released from the reservoir at the constant rate of 0.16 m^3/s. In December 2004, LHDA adjusted the outflow of the reservoir to 25% of the Nqoe River's mean annual flow (i.e. 0.04 m^3/s, (5.05 million m^3/year)), to store more water in the reservoir to augment supplies to downstream towns, including Lesotho's capital city Maseru, during times of drought (LHDA, 2006, 2007). After completion of Phase 2 of the LHWP (due in 2019), an average 70 m^3/s is expected to transit through the `Muela reservoir to South Africa (Lesotho Government, 2011; Ramsingh, Joubert, Geldenhuys & Potgieter, 1998).

2.2. Soil erosion and reservoir sedimentation in the `Muela reservoir catchment

There are no previous publications on soil erosion assessment in the Nqoe River catchment upstream of the `Muela dam. However, based on visual assessment by the LHDA panel of Environmental Experts, some initiatives have been taken by the LHDA together with the `Muela community to curb the suspected high rates of soil erosion in the catchment. The most visible manmade structures that attempt to trap soils that get eroded down the steep slope of the catchment are low-lying rock made terraces (Plate 1).

In Plate 1, the light patches of land on the steep slopes across the valley, such as those areas enclosed in the rectangle (top right), are marginal lands that have been converted to cropland by local communities of the Nqoe catchment. Cultivation of these marginal lands is believed to exacerbate rates of soil erosion within the catchment and thus increase the rate of sediment deposition in the `Muela reservoir. During prolonged rains of autumn, especially in February, localized mud flows may occur from the upper slopes (Plate 2) when the soil becomes saturated, thereby mobilising additional sediment towards the `Muela reservoir.

Analysis of soil samples from the Nqoe River catchment included 1 sample from each are of the medium silt loam, gravelly silt loam and very coarse gravelly silt loam; and 2 samples from the soil type of coarse gravelly silt loam as depicted in Fig. 4(a). Sieve analyses (PSA) of these soil samples yielded the results that are presented in Table 1 below.

Erodibility values for the soil types of the Nqoe catchment soils have not been previously determined. The last row in Table 1 above was computed from silt and clay content using the empirical relationship (Eq. (1)) after Vaezi, Hasanzadeh, and Cerdà (2016).

$$SE = -959 \times 10^{-5} + 66 \times 10^{-5}\,\text{Silt} + 61 \times 10^{-5}\,\text{Clay} \quad (1)$$

Where *SE* is the soil erodibility (kg/ha), and *Silt* and *Clay* are percentage in the soil. This empirical equation explained about 82% of erodibility variance in the soils of the semi-arid North Western Iran for which it was developed, with silt explaining 43% whereas clay contributed 39% to the soil erodibility variance.

Particle size analyses results in Table 1 and the use of soil classification triangle (Vaezi et al., 2016) were also used in the categorization of the soil textural classes of the catchment soil types as depicted in Fig. 4(a). The broad soil texture classes were used with the following particle diameters: clay (0.001–0.004 mm); silt (0.004–0.062 mm); sand (0.062–2.0 mm); and gravel / pebbles (> 2 mm).

2.3. Reservoir survey data

The South African Department of Water Affairs and Forestry (DWAF) commissioned a comprehensive pre-impoundment survey of the Muela reservoir in 1985. This was followed by post-impoundment surveys performed by LHDA in 2001 and 2005 (Stephenson & Associates, 2001, 2005). These were of more limited scale than the pre-impoundment survey however, covering only two thirds of the total area of the reservoir. The surveys were

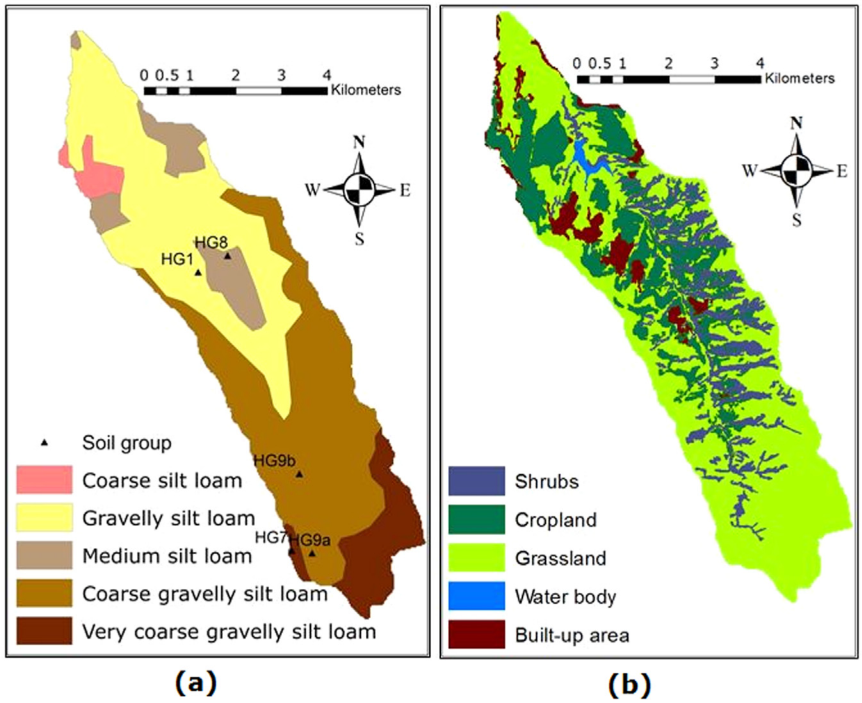

Fig. 4. Soil and Land use / cover maps of the Nqoe River catchment Soil and Land use / cover maps of the Nqoe River catchment, where (a) is Soils (**Source**: Lesotho's Land & Soil Conservation Department, 2014) and (b) is Land use / cover.

Plate 1. Low-lying terraces across steep slopes of the Nqoe River catchment upstream of the `Muela dam.

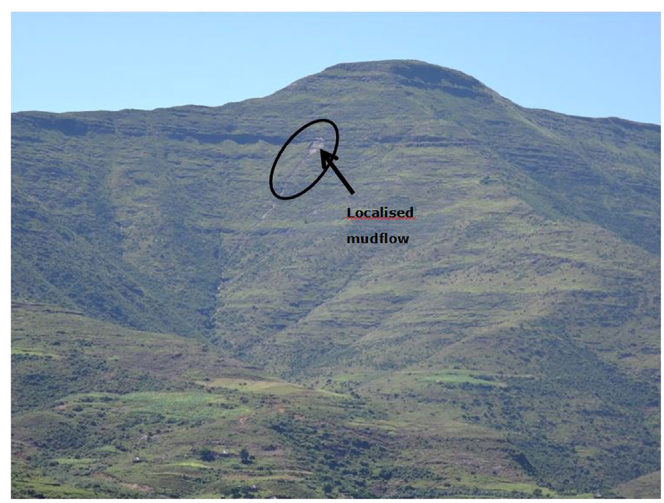

Plate 2. A typical localized mud flows occurring from the steep slope of the Nqoe River catchment upstream of the `Muela dam.

restricted to the areas that were covered by water rather than the area of the reservoir's full supply level (Fig. 5i and ii). In 2007 and 2011 the DWAF commissioned their own post-impoundment surveys following the survey points of their original 1985 survey (Fig. 5iii, iv and v) that included the area beyond the reservoir's full supply level. From the 2007 and 2011 survey data, Jacobs (2011) estimated that there had been an average annual reduction in reservoir volume of 17,500 m^3 since impoundment.

During a field visit at low reservoir supply level, LHDA panel of experts performed simple visual inspection at the southern end of the reservoir in 2009 from which they concluded that the reservoir was undergoing un-estimated and significant sedimentation (Hitchcock, Inambao, Ledger, & Mentis, 2011; Inambao, Ledger, & Mentis, 2010). As a result, additional surveys were commissioned in 2013, 2014 and 2015 (Fig. 5vi, and vii and viii) to obtain a more accurate assessment of sedimentation rates. Unfortunately, similar to the earlier LHDA surveys, these surveys also covered a smaller spatial extent than the DWAF surveys. The challenge to reservoir water managers is to find a consistent methodology for estimation of reservoir volume changes (due to sedimentation) between years, based on an irregular spatial arrangement of survey data.

The number of cross-sections, number of survey points, distance between transects, and ratio of survey area to total transect length for each of the surveys conducted between 1985 and 2015 are summarized in Table 2. It can be seen that whilst the DWAF surveys utilize the same location and number of survey transects, the number of survey points on each transect increases from 1985 to 2011 (from 4203 to 5967). By comparison the early LHDA surveys had much fewer transects. The later LHDA surveys have both a greater number of transects and survey points.

In addition to the raw survey data, the 30 m ASTER-GDEM data (METI & NASA, 2014) and the 1784 m contour (Fig. 6i and ii) were used to extend the interpolation area to at least 9 m above the full-supply level (FSL) of 1775 m. The 1784 m contour was used as it

Table 1
Results of sieve analyses and estimated soil erodibility of soil samples from the Nqoe River catchment.

Particle diameter (mm)	HG1 (% finer)	HG7 (% finer)	HG8 (% finer)	HG9a (% finer)	HG9b (% finer)	Assessment method
20	100.0000	100.0000	100.0000	100.0000	100.0000	PSA
12	99.8793	90.9183	99.8539	98.9949	99.1023	Interpolated
10	99.8491	88.6478	99.8174	98.7437	98.8778	PSA
5	99.7540	72.0700	98.4212	86.6983	94.1413	PSA
2	79.9354	51.5996	89.3171	67.0159	79.4584	PSA
1	61.2672	45.5229	77.7316	56.7611	66.4737	PSA
0.62	41.2110	36.6613	55.9436	43.8023	47.4801	Interpolated
0.5	34.8775	33.8629	49.0632	39.7101	41.4821	PSA
0.25	24.1800	27.2795	31.6949	29.1895	28.5594	PSA
0.1	9.2791	12.5782	8.7845	14.0597	11.5847	PSA
0.075	6.4493	7.0734	5.1360	10.7095	8.4428	PSA
0.062	2.7377	2.4795	1.7638	5.0970	3.9845	Interpolated
0.056	1.0247	0.3593	0.2073	2.5067	1.9267	PSA
0.038	0.3206	0.0244	0.0105	1.0350	1.4068	PSA
0.025	0.1839	0.0961	0.0666	0.4583	0.5165	Interpolated
0.004	0.1346	0.1219	0.0867	0.2507	0.1960	Interpolated
0.002	0.0449	0.0406	0.0289	0.0836	0.0653	Interpolated
0.001	0.0000	0.0000	0.0000	0.0000	0.0000	Lower bound
Soil erodibility (Mg ha h MJ^{-1} ha^{-1} mm^{-1})	**0.0244**	**0.0373**	**0.0317**	**0.0335**	**0.0298**	**Calculated**

represents the closest surveyed contour above the full supply level. Contour lines from a 1982 topographic map were also digitized to use in comparison of interpolated DEM and TIN surfaces (Fig. 6iii)). Unfortunately the most easterly section of the reservoir was missing.

3. Methods and materials: interpolation and triangulation of bathymetric data

For comparative cross-checking, two methods were used to estimate the bathymetric surface of the reservoir (Fig. 7): i. construct a Digital Elevation Model (DEM) from survey data, and ii. construct a Triangulated Irregular Network (TIN) surface from the survey data. Four interpolation methods were initially compared including inverse distance weighting; Kriging; natural neighbor; and spline. A constant cell size 1.0×10^{-5} decimal degree was used for all interpolation methods. The TIN method involved construction of a TIN surface for each survey data-set using direct linear interpolation.

Spline interpolation of the survey data was found to produce unrealistic (extreme or out of range) elevation points when used with the smaller survey LHDA data sets. This was especially true where the distance between sampled data points was much greater than the interpolated cell resolution, and where data points were irregularly distributed, for example, the 2013 LHDA survey which consisted of just 292 survey points across an area of 0.4 km^2. Whilst the performance of the spline interpolation could be improved by using smaller interpolated cell size, this method was rejected as unsuitable for comparison with other survey data-sets.

3.1. Comparison of Interpolated and TIN surfaces

DEM (Krigged) and TIN surfaces were first created using digitized points from the 1982 topographic map. These are shown in Fig. 8i and ii respectively, and provide a useful reference for the surfaces interpolated from the survey data.

Fig. 9 illustrates the DEMs produced by Kriging each of the reservoir survey data-sets. It can be see that the interpolation is smoothest for surveys that had both a large number of survey data-points and a large number of transects (e.g. 2015 LHDA survey). The ability of the Kriging interpolation to produce more conservative intermediate values meant that it lent itself to a more regular interpolation of the survey datasets. Differences in TIN surfaces produced from each survey data-set (Fig. 10) exhibited an average bed increase of 1.9 m between 1985 and 2015 at the deepest part of the reservoir.

Table 3 illustrates the maximum difference in depth of each interpolated DEM and TIN surface, with the surface created from the 1982 contour data. It can be seen that each interpolated surface varies with time such that surface estimates are up to 4.6 m higher by 2015 compared to 1985. The variability of the surface interpolated from the surveyed data is a result of the coarse horizontal spatial resolution of the data transects, and the relatively large distances between cross-sections (as the average distance between transects is 48 m in 2015 and is 124 m for the survey transects of 1985, 2007 and 2011).

3.2. Estimation of storage capacity

To estimate the storage capacity of the reservoir, from the interpolated surfaces, elevation values within the reservoir boundary were subtracted from the full-supply level (1775 m asl). These values were then summed, and multiplied by cell area, to obtain storage capacity at the full-supply level. The volume of material under the TIN surface was calculated from the sum of the volumes of the constituent triangular prisms. The difference between estimated volume of the reservoir for the three DWAF surveys indicated a gradual linear decrease in capacity from 5.935 million m^3 in 1985 to 5.555 and 4.978 million m^3 in 2007 and 2011, respectively. When the same survey data by the DWAF is subjected to different volumes and interpolation estimation using the DEM - Kriging and TIN approaches in ArcGIS10x yield varied but slightly lower volumes as presented in Tables 3–5, but the downward linear trends in estimated volumes are maintained. Volumes in survey data from other sources are erratic with no clear trends as the surveyed transects vary slightly from year to year and are only restricted to inundated areas that also vary (Fig. 5). For instance, DEM-Kriging volume computations from the surveys by Stephenson & Associates & (, 2001, 2005) and the 1784 m contour line yielded increasing trend in reservoir volume from 4.02 in 2001 to 4.51 million m^3 in 2005, whereas the TIN volumes are from 3.35 to 4.38 million m^3 in 2001 and 2005, respectively (Tables 3–5).

The creation of DEM and TIN surfaces (based on the surveyed the surveyed data together with the 1784 m contour data)

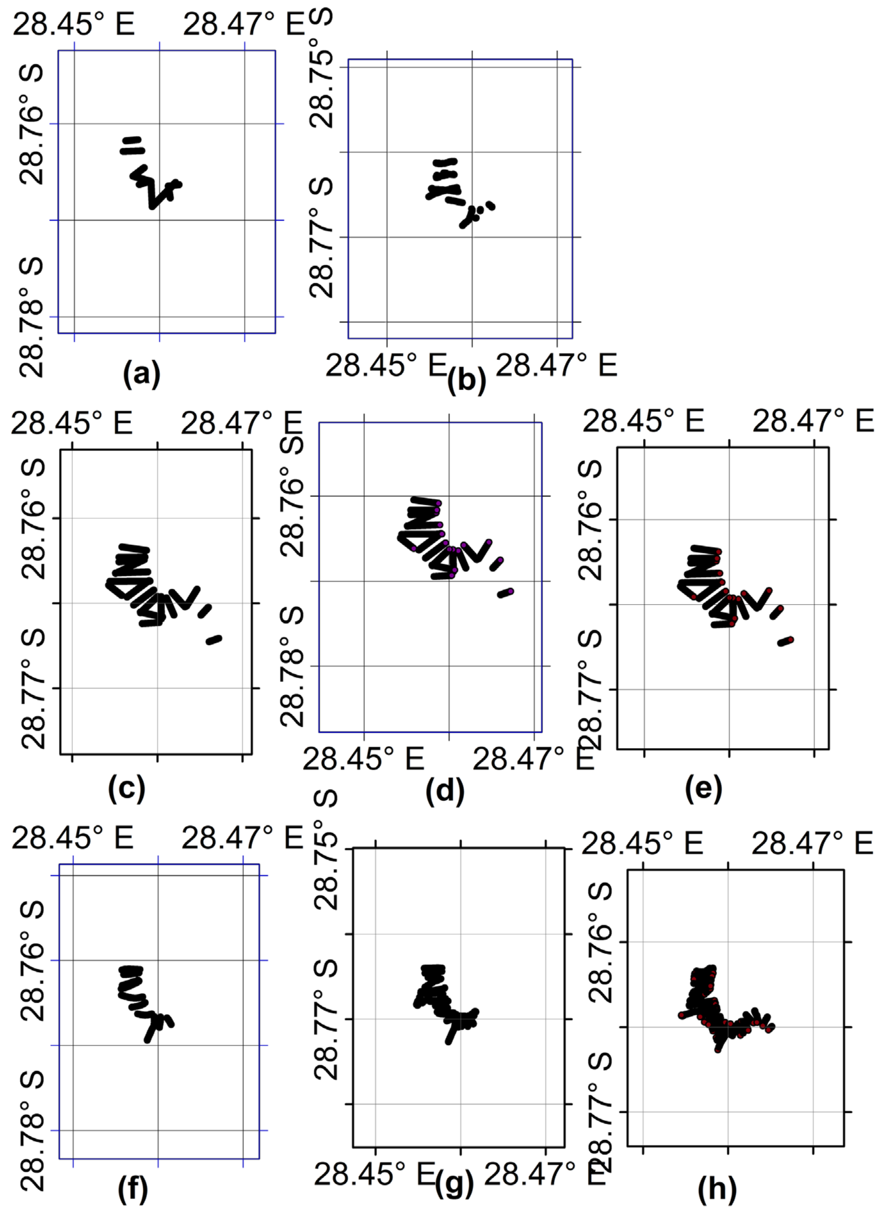

Fig. 5. Elevation data used in derivation of DEM and TIN bathymetry, where: (a) 2001 LHDA survey; (b) 2005 LHDA survey; (c) 1985 DWAF survey; (d) 2007 DWAF survey; (e) 2011 DWAF survey; (f) 2013 LHDA survey; (g) 2014 LHDA survey; (h) 2015 LHDA survey).

Table 2
Summary of survey data used as basis for reservoir capacity calculation.

Year	Number of transects	Total number of survey points	Distance between transects (m)	Area/transect length (m^2/m)	Source
2015	32	2083	48	36	LHDA
2014	18	910	55	37	LHDA (and this study)
2013	10	292	99	77	LHDA
2011	18	5967	124	85	DWAF (Jacobs, 2011)
2007	18	5718	124	85	DWAF (Jacobs, 2011)
2005	7	162	137	93	LHDA (Stephenson & Associates, 2005)
2001	9	2373	101	76	LHDA (Stephenson & Associates, 2001)
1985	18	4203	124	85	DWAF (Jacobs, 2011)

presented in Figs. 9 and 10 was repeated but with the exclusion of the 1784 m contour data but inclusion of the ASTER-GDEM data (for areas outside the perimeter of the survey but within the reservoir area), and then with the inclusion of both the 1784 m contour and the ASTER-GDEM data. The resulting volumes estimated from each survey data-set are shown in Tables 4–6 respectively. It can be seen that using the additional ASTER-GDEM data has the effect of increasing reservoir volume as the interpolated area becomes unbounded around the reservoir perimeter. The effect is seen in both the constructed DEM and TIN. It can also be seen from the data that the interpolated DEM always gives a higher estimated volume than the TIN due to the less accurate

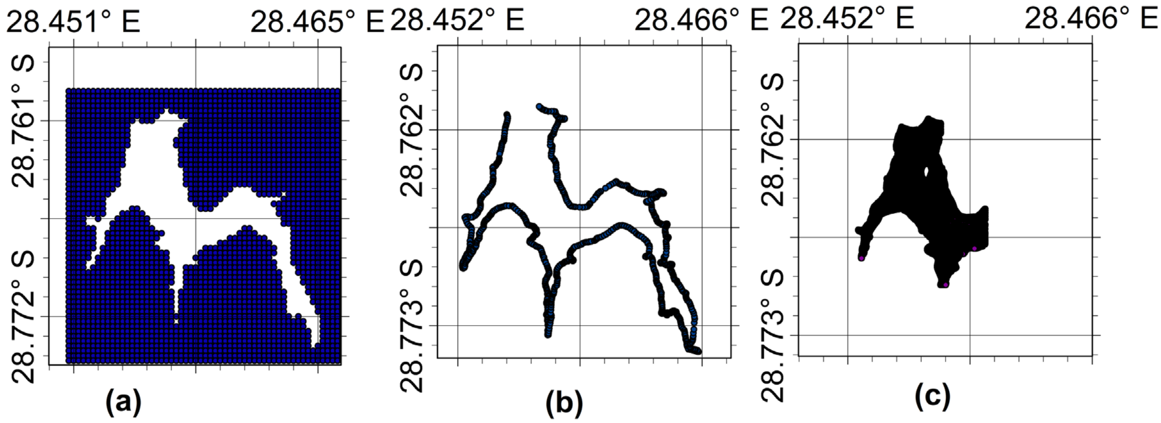

Fig. 6. (a) ASTER-GDEM elevation data (b) 1784 m contour, and (c) the 1984 contour used in interpolation of survey data.

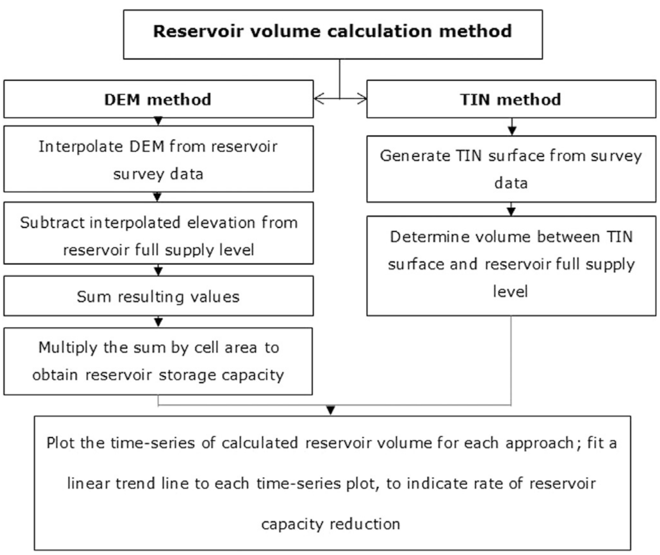

Fig. 7. Procedure for calculating reservoir volume from surveyed points.

representation of surface bathymetry. The volume predicted using both contour data and the ASTER-DEM is actually similar to the volumes predicted using just the contour data, suggesting that if the ASTER GDEM data was unavailable, reliable estimates can still be made if the boundary contour data is available.

3.3. Comparison of interpolation methods

The DEM interpolation procedure (with contour and ASTER-DEM) was repeated using inverse distance weighting and natural neighbor methods. The results, illustrated in Fig. 11 illustrates that the nearest neighbor interpolation method predicts consistently lower reservoir volumes than the other interpolation and TIN surface creation methods. By contrast Kriging and IDW interpolation methods gave the highest reservoir volume estimates; the IDW method producing highest estimates only when the ASTER-GDEM boundary data was used. Natural neighbor and IDW interpolation methods were less sensitive to changes in the total number of data points and interpolated cell size.

The difference between the interpolated (Kriging) DEM surfaces and the 1985 DWAF interpolated survey data are shown in Fig. 12. The 2007 and 2011 interpolated surfaces indicate greater sediment deposition in the mid-western part of the reservoir, and greater sediment erosion in the north, south and eastern sections. All other surveys also indicate greatest sediment deposition in the middle sections of the reservoir and erosion in the north-west and south-west.

Fig. 13 depicts estimated sediment built-up since the pre-impoundment survey in by DWAF in 1985. This is calculated as the difference between 1985 elevation and elevation in each surveyed year. Results are shown for estimates made using the Krigged DEM and the TIN surface estimates for each survey year.

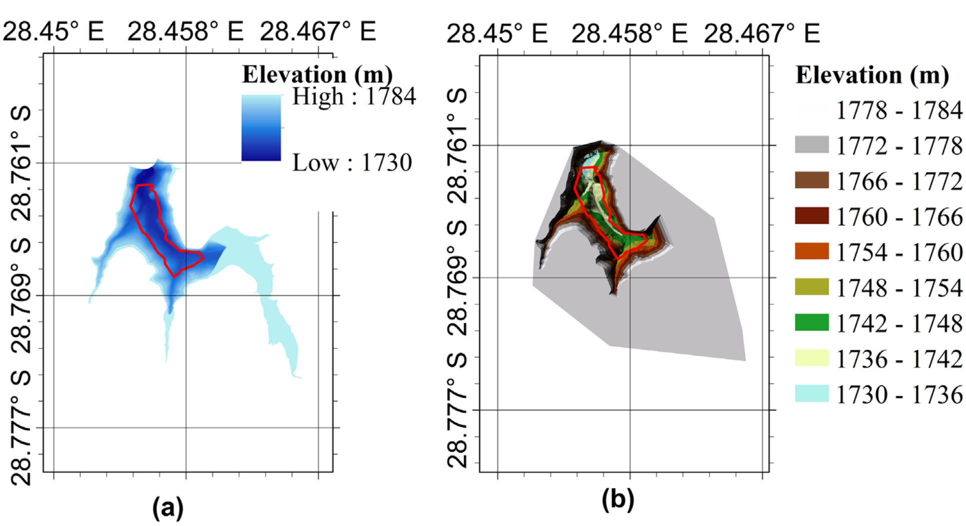

Fig. 8. (a) Constructed DEM (Kriged) and (b) TIN surface for the 1982 contour data (position of the area covered in all years of surveys data indicated for reference).

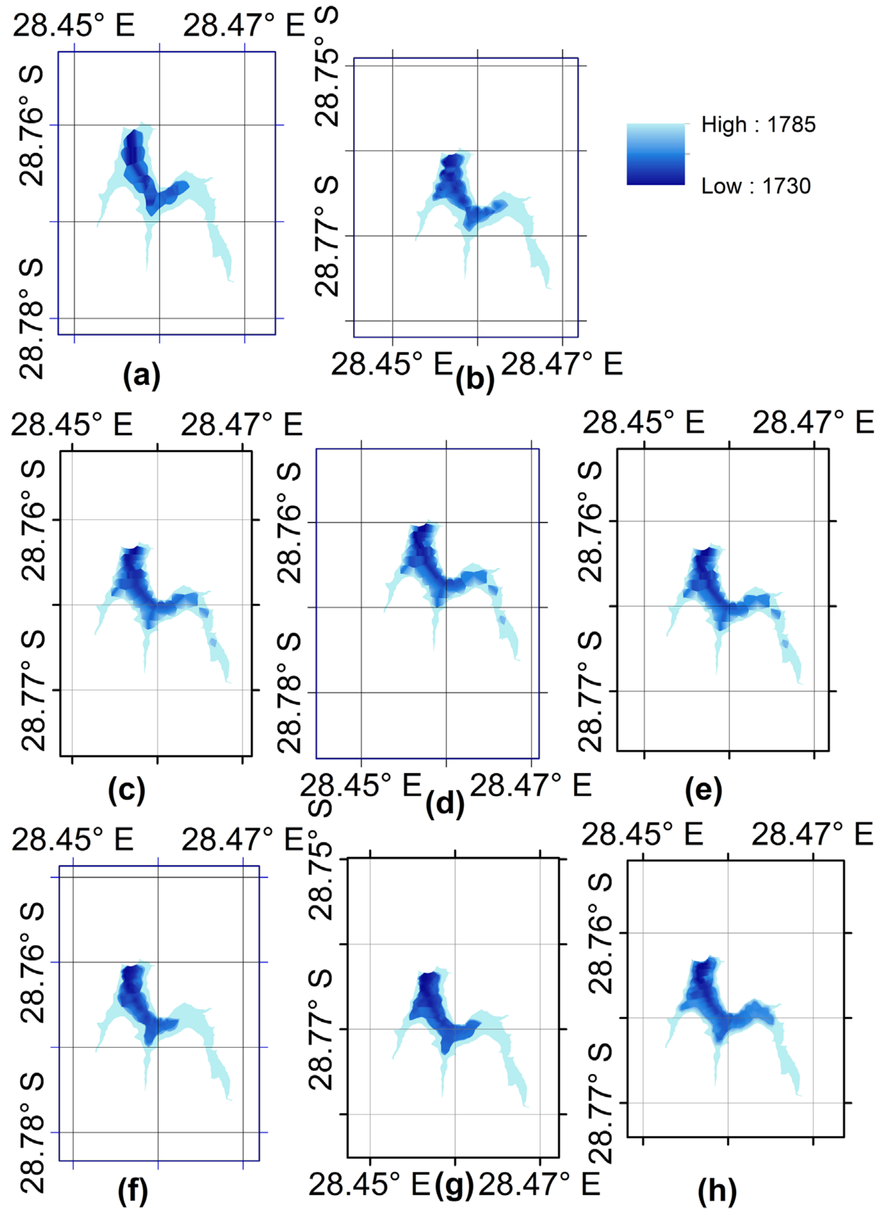

Fig. 9. DEMs derived using Kriging interpolation with DWAF (1985, 2007, 2011) and LHDA (2001, 2005, 2013, 2014, 2015) survey data sets, where: (a) 2001 LHDA survey; (b) 2005 LHDA survey; (c) 1985 DWAF survey; (d) 2007 DWAF survey; (e) 2011 DWAF survey; (f) 2013 LHDA survey; (g) 2014 LHDA survey; (h) 2015 LHDA survey).

4. Results and discussion

Fig. 13 suggests that there has been an increasing trend in sediment deposition in the reservoir since 1985. Closer observation of Krigged DEMs of each survey data set suggests that actual rates of sediment deposition varied spatially between each survey. This general trend was indicated irrespective of which interpolation method was used, and is also seen in the raw survey data.

The large increase in deposition indicated between 1985 and 2001 may be due to the reduction in survey transects (eighteen to nine). However, more information about the reservoir's outflow and transfer records is needed, as periods of sediment erosion in the reservoir may be related to periods of reservoir flushing. If data survey by DWAF in 1985, 2007 and 2011 (Fig. 11), is looked at in isolation however a steady linear decrease in the reservoir's volume over time at the rate of approximately 17,500 m^3 per year can be identified.

The average rate of reduction in volume of the `Muela reservoir between 1985 and early 2015, is 15,400 m^3/year (based on Kriging DEM). Inter-annual variability in reservoir storage capacity reduction rates vary between 11,400 m^3/year and 18,200 m^3/year, based on IDW DEM and TIN, respectively, or 18,100 m^3/year based on the natural neighbor DEM. Whilst these estimates provide an indication of the trend of reservoir volume reduction due to sedimentation, there is still a large degree of uncertainty due to errors introduced during creation of the bathymetric surface measurement. In addition, errors will also have been made during the initial survey, including collimation errors (Mishra, 2014); parallax errors (GIA, 2006); and sampling errors.

4.1. *Impact of data resolution on reservoir volume estimates*

Surveys completed after 2001 are of lower resolution than the 1985 survey and as a result will introduce uncertainty in estimates of bathymetric change. Where the produced DEM is concave (for example at the valley bottom), and survey points or cross-sections are further apart, over-estimation of the bathymetric surface may result. Conversely, where convex slopes are represented under-estimation may occur.

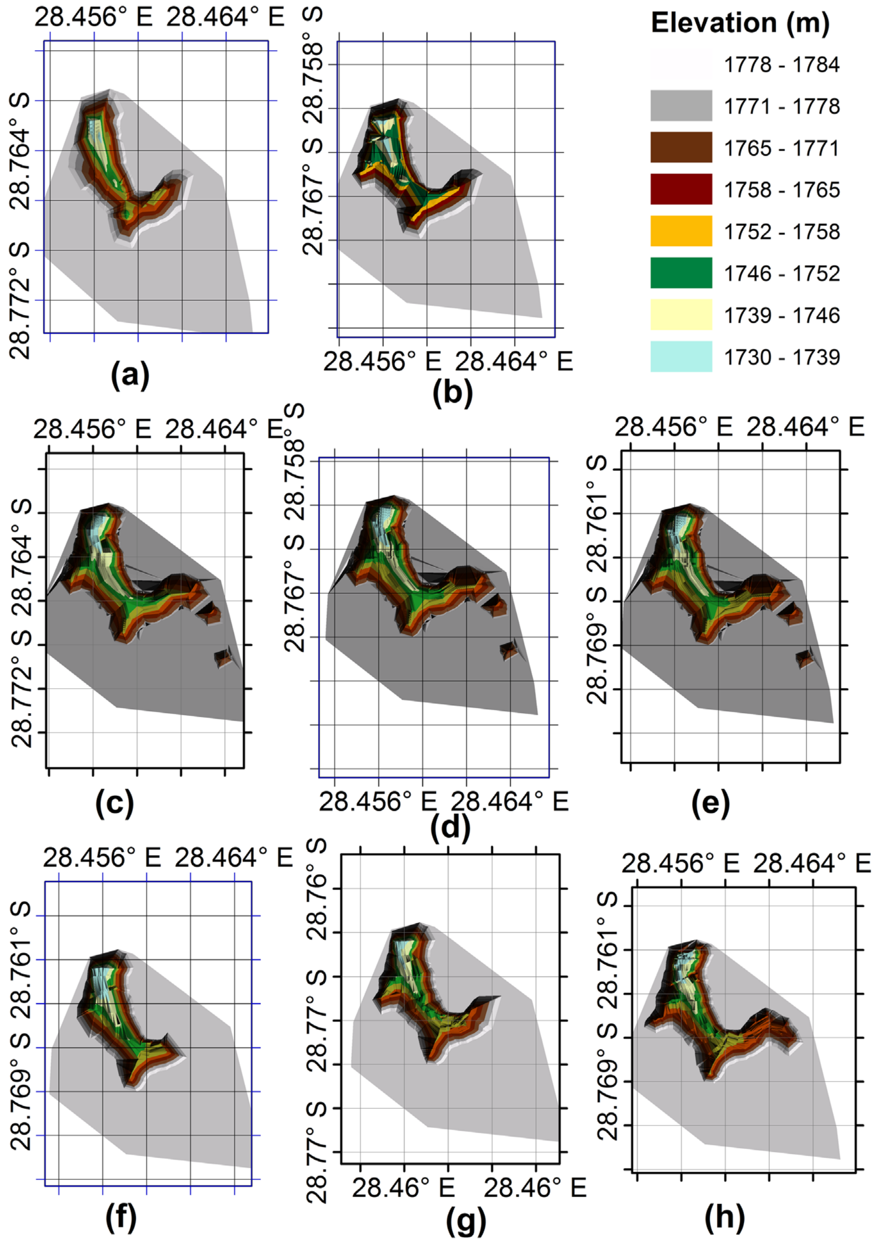

Fig. 10. TINs derived for each DWAF (1985, 2007, 2011) and LHDA (2001, 2005, 2013, 2014, 2015) survey data set, where: (a) 2001 LHDA survey; (b) 2005 LHDA survey; (c) 1985 DWAF survey; (d) 2007 DWAF survey; (e) 2011 DWAF survey; (f) 2013 LHDA survey; (g) 2014 LHDA survey; (h) 2015 LHDA survey).

Table 3
Maximum change in depth of interpolated DEM and TIN surfaces produced from survey data relative to the surface created from the 1982 contour data (shaded data indicates DWAF surveys).

		1985	2001	2005	2007	2011	2013	2014	2015
Max Δ Depth (m)	**DEM**	1.1	3.5	3.4	3.7	5.8	5.4	5.0	4.6
	TIN	0.7	3.5	2.9	3.7	3.7	5.3	2.2	2.6

Table 4
Reservoir volume at full supply level estimated using the 1974 m contour.

Interpolation method	Estimated Reservoir Volume (MCM)							
	1985	2001	2005	2007	2011	2013	2014	2015
Kriging	5.40	4.02	4.51	5.03	4.94	4.38	5.16	5.59
TIN	5.30	3.35	4.38	4.90	4,80	4.18	4,69	5.16

Table 5
Reservoir volume to full supply level estimated using the ASTER GDEM data.

Interpolation method	Estimated Reservoir Volume (MCM)							
	1985	2001	2005	2007	2011	2013	2014	2015
Kriging	5.57	4.67	5.18	5.19	5.10	5.10	5.61	5.94
TIN	5.47	3.91	4.98	5.07	4.98	4.71	5.07	5.59

Table 6
Reservoir volume to full supply level estimated using the 1784 m and ASTER GDEM data.

Interpolation method	Estimated Reservoir Volume (MCM)							
	1985	2001	2005	2007	2011	2013	2014	2015
Kriging	5.42	4.09	4.33	5.01	4.92	4.32	5.03	5.49
TIN	5.31	3.36	4.39	4.90	4.80	4.18	4.70	5.21

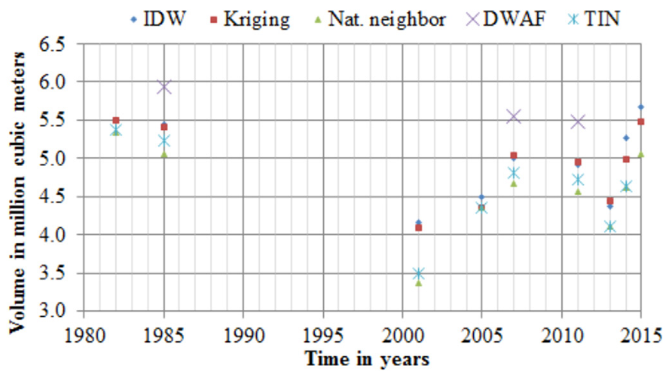

Fig. 11. Reservoir volume calculated from survey data; reference 1784 m contour; and the ASTER GDEM.

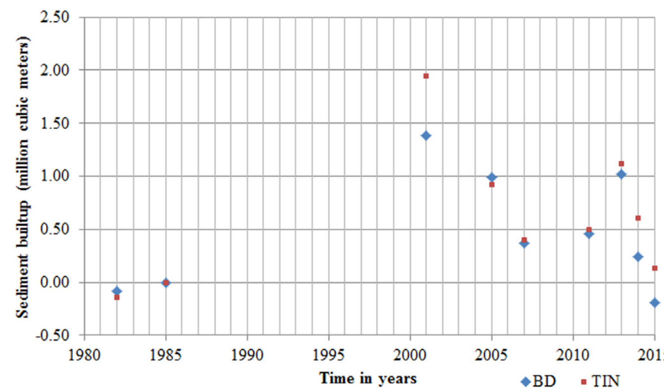

Fig. 13. Sediment build-up calculated from interpolated (DEM) and TIN surface bathymetry.

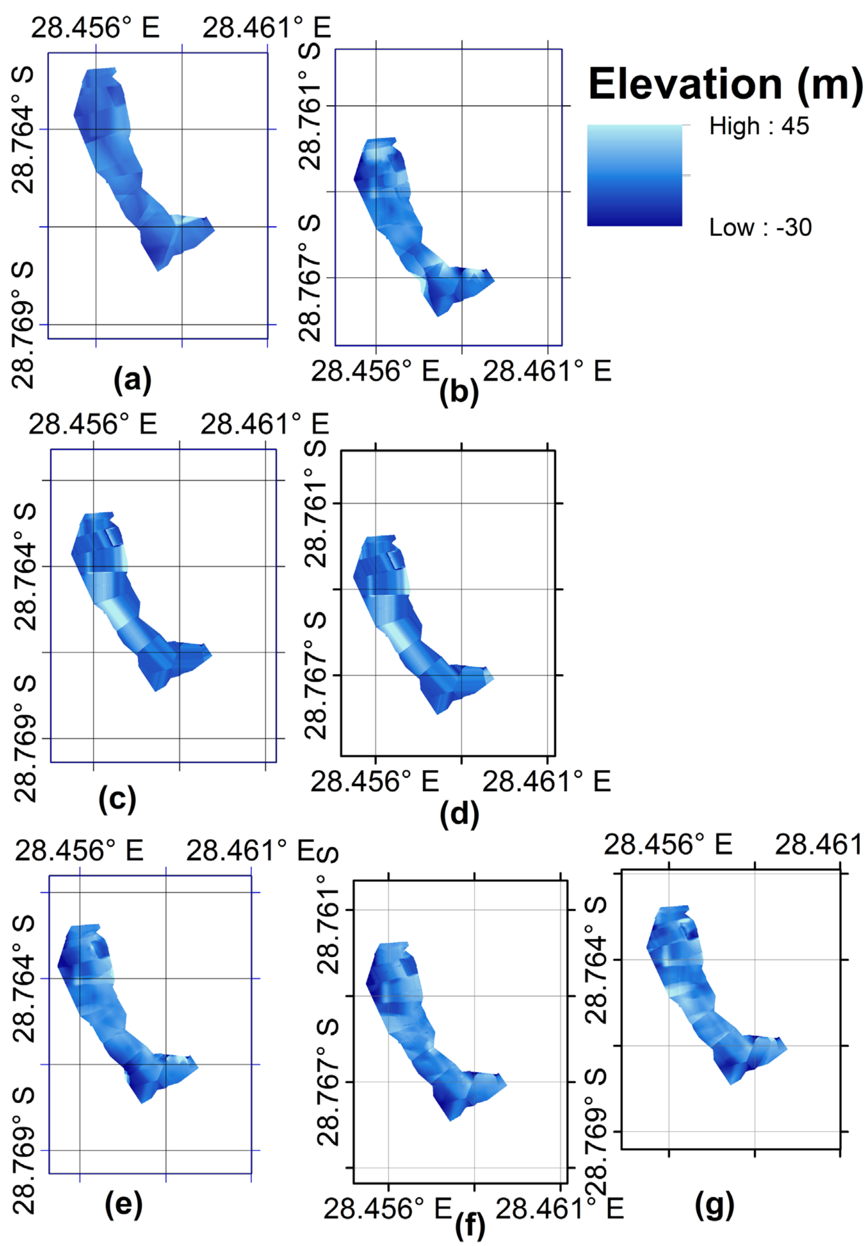

Fig. 12. Change in interpolated DEM compared to surface DEM produced from 1985 DWAF survey, where: (a) 2001 LHDA survey; (b) 2005 LHDA survey; (c) 2007 DWAF survey; (d) 2011 DWAF survey; (e) 2013 LHDA survey; (f) 2014 LHDA survey; (g) 2015 LHDA survey.

The increase in bathymetric surface height calculated between the two pre-impoundment survey years of 1982 and 1985 (Table 3) is due to the generalization of the higher density survey from the 1 m interval contours, thereby introducing errors that lead to over-estimation of the land surface elevation. Representation of the two surfaces can be seen to be more accurate in the TIN surface than the Krigged surface.

The DEM generation from the survey data was performed directly on the irregularly spaced survey point data. Despite the Kriging approach producing reasonable results and being effectively used in previous studies (Alcântara et al., 2010; Gibbings & Raine, 2005), use of this method becomes computationally impractical when the number of surveyed data points exceeds half a million. This is due the heavy computation requirement for executing the Kriging semi-variogram and in the case required interpolation at a less accurate lower resolution than would be ideal. It should be ensured however that interpolation resolution is finer than the survey data, otherwise areas where data density is greater than the interpolation cell resolution will occur. The conflict between interpolation resolution and density of survey points also caused the spline interpolation method to fail.

5. Conclusion

Changes in reservoir storage capacity, and thus sedimentation volume is relatively easy and implement using GIS, however, caution should be used in interpretation of the results as there are numerous sources of error that can influence results. Three interpolation methods: inverse distance weighting, natural neighbor and Kriging were used in this study. Whilst Kriging proved to be more computationally demanding than the other two methods, it generally produced more satisfactory results. The spline method proved to be unsuitable for this exercise as it was prone to produce values beyond the ranged of surveyed data. Production of a TIN surface was both relatively easy to implement and accurate and hence is recommended for similar exercises.

Analysis of DWAF's raw survey data from the `Muela reservoir indicated a steady linear decrease in reservoir storage capacity of approximately 17,500 m^3 /year. Although this suggests that sedimentation in the reservoir is not significant, it is recommended that it should be monitored with regular survey. Such survey should be completed using repeatable survey locations and transects, and across the same spatial extent and at the same resolution as previous survey. It has been illustrated in this study that comparison of survey data from different locations yields inconclusive results with varying degrees of uncertainly. The LHDA surveys for example were less compatible with the DWAF survey data and as a result predicted sediment deposition rates lower than those trend predicted by the three DWAF surveys. In addition, it is suggested that information related to water transfer and releases from the reservoir should also be reviewed when assessing sedimentation rates, to identify larger water release events and associated sediment flushing.

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References

Alcântara, E., Novo, E., Stech, J., Assireu, A., Nascimento, R., Lorenzzetti, J., et al. (2010). Integrating historical topographic maps and SRTM data to derive the bathymetry of a tropical reservoir. *Journal of Hydrology*, *389*(3–4), 311–316.

Arthur, L. J., Wagner, C. M., & Hein, B. (1997). Lesotho highlands water project - design of the 'Muela hydropower station. *Proceedings of the Institution of Civil Engineers*, *120*(5), 43–53.

Bailey, A. (2013). *The orange–senqu river basin infrastructure catalogue*. United Nations Development Programme (UNDP). United Nations Office for Project Services (UNOPS). Centurion: ORASECOM.

Chakela, Q. K. (1981). *Soil erosion and reservoir sedimentation in Lesotho*. Uppsala, Uppsala, Sweden: Uppsala University.

DWAF (2014). *Lesotho highlands water project (LHWP): Key statistics*. Retrieved 04 28, 2014, from Department of Water Affairs - Republic of South Africa: ⟨http://www.dwaf.gov.za/orange/up_orange/lhwpstat.aspx⟩.

Evans, J. E., Levine, N. S., Roberts, S. J., Gottgens, J. F., & Newman, D. M. (2002). Assessment using GIS and sediment routing of the proposed removal of Ballville Dam, Sandusky River, Ohio. *Journal of the American Water Resources Association*, *38*(6), 1549–1565.

GIA (2006). *How things work: consider sources of error when trigonomentric leveling with total stations*. Frederick, Maryland: Flatdog Media, Inc. ⟨http://www.profsurv.com/magazine/article.aspx?i=1736⟩.

Gibbings, P., & Raine, S. (2005). Evaluation of a hydrographic technique to measure on-farm water storage volumes. *Agricultural Water Management*, *78*(3), 209–221.

Hitchcock, R., Inambao, A., Ledger, J., & Mentis, M. (2011). *Lesotho highlands water project - Report 58. Lesotho Highlands Development Authority, Environmental Panel of Experts*. Maseru: LHDA.

Inambao, A., Ledger, J., & Mentis, M. (2010). *Lesotho highlands water project - Report 56. Lesotho Highlands Development Authority, Panel of Environmental Experts*. Maseru: LHDA.

Jacobs, J. (2011). *Capacity determination of Muela Dam 2011. Directorate Spatial and Land Information Management, Department of Water Affairs, Private Bag X313, Pretoria 0001*. Pretoria: Department of Water Affairs - Directorate Spatial and Land Information Management.

Land and Soil Conservation Department (2014). *The Lesotho soil associations map: Lesotho Land and Soil Conservation Department. The Lesotho Soil Associations Map*. Maseru, Lesotho: Lesotho Government.

Lesotho Government (2011). *Lesotho High Commission in London, United Kingdom*. (L. H. Commission, Editor, L. H. Commission, Producer, & KD Web) Retrieved 06 14, 2014, from Water and Energy: ⟨http://www.lesotholondon.org.uk/water⟩.

Levec, F., & Skinner, A. (2004). *Manual of instructions: Bathymetric surveys*. Ontario: Ministry of Natural Resources.

LHDA (2003). *Lesotho highlands water project phase 1 policy for instream flow requirements*. Maseru: LHDA.

LHDA (2006). *Annual flow releases - Instream Flow Requirement (IFR) Implementation and Monitoring (October 2004 to September 2005). Lesotho Highlands Development Authority, Hydrology, Aquatic Systems Section; Monitoring and Evaluation Branch*. Maseru: LHDA.

LHDA (2007). *Annual flow releases - instream flow requirement (IFR) implementation and monitoring (October 2005 to September 2006). Lesotho Highlands Development Authority, Hydrology - Aquatic Systems Section; Monitoring and Evaluation Branch*. Maseru: LHDA.

LHDA. (2014). PRESS RELEASE - Unveiling ceremony at Tlokoeng launches Phase II of the Lesotho Highlands Water Project. Lesotho Highlands Development Authority. Maseru: Lesotho Highlands Development Authority.

Matete, M. E. (2004, May). The ecological economics of inter-basin water transfers: The case of the Lesotho Highlands Water Project (Ph.D. thesis). (U. o. Pretoria, Ed.) Pretoria, Gauteng, South Africa. (Unpublished Ph.D. thesis).

METI, & NASA (2014). Reverb: ECHO. Retrieved 03 16, 2014, from ⟨http://reverb.echo.nasa.gov/reverb/#utf8=%E2%9C%93&spatial_map=satellite&spatial_type=rectangle&keywords=aster%20gdem&selected=C197265171-LPDAAC_ECS⟩.

Mishra, G. (2014). *Surveying: error sources in total station*. (The Constructor) Retrieved 06 12, 2014, from The Constructor: ⟨http://theconstructor.org/surveying/error-sources-in-total-station/6052/⟩.

Ortt, R. A., VanRyswick, S., & Wells, D. (2007). *Bathymetry and sediment accumulation of Triadelphia and Rocky gorge reservoirs*. Maryland: Department of Natural Resources, Watershed serives, Maryland Geological Survey.

Panagos, P., Jones, A., Bosco, C., & Senthil, K. P. (2011). European digital archive on soil maps (EuDASM): Preserving important soil data for public free access. *International Journal of Digital Earth*, *4*(5), 434–443.

Ramsingh, L., Joubert, H., Geldenhuys, J., & Potgieter, M. (1998). *Determination of the effect of Lesotho highlands water on the Vaal Dam*. Vereeniging, Gauteng, South Aftrica: Rand Water.

Showers, K. B. (2005). *Imperial gullies: Soil erosion and conservation in Lesotho. (Vol. Series in Ecology and History)*. Athens, Ohio, USA: Ohio University Press.

Stephenson & Associates (2001). Year 2001 sediment survey of Katse and 'Muela Reservoir - Final Report. LHDA.

Stephenson and Associates (2005). Year 2005 Sediment Survey of Katse and 'Muela Reservoir - Final Report. Consultancy Report, LHDA.

Vaezi, A. R., Hasanzadeh, H., & Cerdà, A. (2016). Developing an erodibility triangle for soil textures in semi-arid regions, NW Iran. *CATENA*, *142*, 221–232.

Wallis, S. (1992). *Lesotho highlands water project*. Macclesfield: Laserline UK.