Evaluation of a hydrographic technique to measure on-farm water storage volumes

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ABSTRACT

Digital terrain models of on-farm water storages are required to assist in accurately measuring the on-farm water balance and water use efficiency components including storage capacity, inflow, seepage, evaporation and discharge volumes. A hydrographic surveying system combining a high-precision global positioning system (GPS) and a low-cost depth sounder was developed to facilitate the creation of a digital terrain model. The system was validated by comparing the hydrographic terrain model and volume measurements against both a traditional real time kinematic (RTK) land based survey and independent lead line depth measurements. Flat bottomed storage volumes were measured with errors of less than 1% using the hydrographic survey technique. A major proportion of the error in small storages was found to be associated with the ability to accurately identify the inflection point between the banks and floor of the storage. However, for larger storages, errors were primarily related to density of sampling points within the storage floor area. Recommendations are provided regarding the appropriate measurement procedures, including sampling point density, for a range of storage sizes.

ADDITIONAL KEYWORDS: Dam, farm, survey, irrigation, efficiency, GPS

INTRODUCTION

Improving the efficiency of water use is a major issue particularly in the irrigated agricultural sector. Over the last thirty years, there has been a considerable investment in on-farm water storages within eastern Australia. The current capacity of Queensland's on-farm dams alone is approximately 2.5 million megalitres (ML). Many of these storages are ring tanks with either a continuous circular or square embankment built of earthen material extracted from within the storage. These storages are typically flat bottomed and range in size from less than 50 ML to approximately 60000 ML with the majority of dam embankments being less than 5 m in height.

A major impediment to improving on-farm water use efficiency is the lack of accurate on-farm water management records. Measuring whole farm water balance volumes is an important first step to improving irrigation management and optimising water use efficiency (Hearn, 1998; Raine, 1999). Accurately measuring the volume of water in on-farm storages is also an important precursor to planning the area of crop to be planted and assessing irrigation management options.

The capacities and depth-volume relationships of many on-farm water storages in Australia are not accurately known and the measurement of inflow and outflows is often difficult or not routinely undertaken. One of the simplest and most accurate methods of determining a change in water storage volume is to monitor storage water level and correlate this to stored water volume. Changes in the water depth over time can then be used to estimate the volume of water that has been captured as either overland flow or tail-water recycling, or used to estimate the volume of water applied to fields and as an input in calculating water use efficiencies.

Calculation of water volumes in storages requires accurate topographical measurements of the storage facility. These measurements may be obtained when the storage is empty using traditional land surveying techniques (e.g. Clark, 1972) but this is not a common practice in the region. Dam storage volumes may also be calculated from inflow and outflow measurements. However, to obtain the depth-volume relationship over the full storage volume using inflow measurements requires the dam to be completely emptied and filled.

Hence, depending on storage management practices, it may not be possible to use either of these methods in a timely manner.

A range of hydrographic methods have been used in the marine environment to model sea floor topographic features (e.g. Ingham and Abbott, 1992). For example, side-scan sonar has been widely used for over thirty years in the marine environment to produce detailed images of the sea floor at resolutions up to twenty centimetres (California Marine Habitat Task Force, 1999). Optical techniques (e.g. laser line-scanners and multi-spectral imaging) are also available but are limited in their depth range by water clarity (California Marine Habitat Task Force, 1999). However, most of these methods are not suitable for mapping on-farm storages because of the high costs (e.g. up to approximately AUD300000 or USD230000) involved, and the geographic nature and small scale of many on-farm storages.

Echo sounding has also been used (e.g. Hughes & Taube, 2000) to measure water depths. In its simplest form, a sound pulse is transmitted from the echo sounder (transducer) at the water surface, bounced off the underwater 'floor' and received back at the transducer (Gardner et al., 2000). The time lapse between sending the sound pulse and receiving the echo is used, along with the speed of sound in water, to calculate the depth at that point. This technique has been used to map regional water storages. For example, Nazaretian (2003) mapped a regional storage with a shoreline of 483 km and a surface area of 13840 ha using a transducer costing AUD25000 (~USD19000) and kriging software costing approximately AUD250000 (~USD192000). However, the high cost involved prohibits the use of this system for mapping comparatively small on-farm storages.

The recent development of low cost depth sounders that can be linked with global positioning system (GPS) technology has created the potential to use echo sounding as a viable method of mapping on-farm storage surfaces. However, the use of echo sounding for underwater surface mapping is considered to be a more complex (and potentially less accurate) task than undertaking a land survey by conventional methods (Scarfe, 2002).

Kielland and Hagglund (1995) suggested that the two main sources of error in hydrographic surveys are due to the spatial spread of soundings (also noted by Clark, 1972) and errors in the distance and location measurement of individual soundings. The error due to the spatial spread of soundings is caused because the underwater surface is represented abstractly by individual points connected with planar surfaces. Hence, the magnitude of this error is a function of both the unevenness of the underwater surface, and the location and spacing of the representative points. The error in the measurement of the soundings is primarily due to inadequate sounder calibration and errors in the recorded positions. Given the nature of these errors, the aim of this research was to evaluate the potential to use a low cost hydrographic technique to map the surfaces of an on-farm water storage and evaluate the accuracy and precision of the derived digital terrain model (DTM) and calculated volumes.

MATERIALS AND METHODS

Selected storage site

A newly constructed 132 ML water storage (approximately 100 m x 300 m x 5 m depth) located near Stanthorpe, in southern Queensland was selected for this study. The floor and wall surfaces of the storage were surveyed using a conventional real time kinematic (RTK) global positioning system (GPS) based land surveying technique before the storage was filled with water. A DTM (Figure 1) was then created using TerraModel (Trimble Navigation, Christchurch) land surveying software. This DTM was the 'truth' against which the hydrographic measurements were subsequently compared. It was also used to calculate the depth-volume storage relationship at depth increments of 100 mm.

INSERT FIGURE 1 ABOUT HERE

Hydrographic equipment and operation

A three metre aluminium boat was fitted with an inexpensive (~AUD300 or ~USD230) transom mounted electronic depth sounder (P66 Smart, Airmar Technology Corporation) operating at 235kHz with a 6° beam width. A GPS antenna (Ruggedised L1/L2 with ground plane, Trimble Navigation) was mounted above the depth sounder on a pole that allowed both vertical and tilt adjustment to keep the pole directly above the transducer (Figure 2).

INSERT FIGURE 2 ABOUT HERE

The depth sounder was calibrated on site to reduce the impact of water quality and temperature variations. Calibration involved lowering a metal plate to a known depth directly under the transducer. The depth sounder readings taken at a shallow depth (approximately 0.4 m) were used to calculate a constant offset value while calibration in deep water (approximately 4.5 m) was used to calculate a scale factor to apply to the depth sounder measurements. All measurements were taken when the water level was approximately 50% of the overflow level.

HYDROpro software (Trimble Navigation, Christchurch) was used for navigation and data storage in a similar configuration to that described by O'Connell (2003) and Nazaretian (2003). A latency correction factor, which ensures the GPS position corresponds to the location where the depth was measured, was calculated from the difference in offset when the same transect across the storage was measured at the same speed in opposite directions (see Gibbings & Raine, 2004). This latency correction factor was subsequently applied within the HYDROpro software to each of the hydrographic observations. The three-dimensional position of the measured storage surface was obtained for each depth sounding measurement by combining the three-dimensional position of the GPS antenna, the distance of the depth sounder below the GPS antenna, and the depth sounding distance.

The boat was initially navigated twice around the inside of the storage water line while logging measurements. The first circuit was as close as practical to the water's edge while the second circuit was approximately 10-20m away from the water's edge. Parallel transect lines were then navigated across the storage and depths were measured at fixed distances along these transects (see Figure 3). Three independent sets of hydrographic measurements were taken using different transect and point spacings:

(a) 10 metre transect spacing and 5 metre point spacings along the transect lines;
(b) 20 metre transect spacing and 10 metre point spacings along the transect lines; and
(c) 20 metre transect spacing and 20 metre point spacings along the transect lines.

INSERT FIGURE 3 ABOUT HERE

Regardless of how the underwater surface is mapped, a land based survey of the water level and above-water surface (ie. the dry bank area) is required to enable the creation of a

DTM for the full storage volume. In this study, the above-water surface of the storage was surveyed using the same RTK GPS technique used in the land based survey of the storage. Three-dimensional measurements of the surface above the water line of the storage were combined with each of the three independent sets of hydrographic measurements to create three separate DTMs of the storage.

Evaluation of the hydrographic survey technique

The DTMs and volumes obtained for each of the three sets of hydrographic data were compared against the original land survey based DTM. The accuracies of the hydrographic component of the DTMs were also checked by measuring point depths with a suitably weighted and calibrated tape (lead line). Twenty-four lead line depth measurements and horizontal GPS positions were measured in a random pattern across the storage with intervals of approximately 35 m. The lead line levels were used to evaluate the empirical accuracy of both the original RTK GPS land based DTM, and the hydrographic measurements with their associated DTMs.

Differences between the point levels interpolated from the DTMs and the lead line drop levels provided a combined measure of the residual errors involved in the survey methodology, DTM interpolation and lead line drop processes. The average height difference provides an estimate of the accuracy of the DTM while the root mean square (RMS) value provides an estimate of the precision of these elements. The effect of storage water level on volumetric accuracy of the hydrographic survey was assessed by comparing the percentage difference in the water volumes calculated using each of the three independent hydrographic DTMs against the volume calculated using the land based survey DTM.

Effect of sampling point density on DTM accuracy

To evaluate the impact of sampling point density on the DTM accuracy, the points from each individual hydrographic data set were filtered to simulate collecting data at different combinations of point (5, 10, 20 and 40 m) and transect (10, 20 and 40 m) spacings. While filtering was undertaken for a range of spacing combinations, not all combinations were processed. For example, a DTM containing 10 metre point and 10 metre transect spacings was created by deleting every second point in the data set collected at 5 metre point and 10 metre transect spacings. However, depending on which starting point was selected, two combinations of data were possible, which could lead to two different DTMs. In such cases, only one of the possible combinations was arbitrarily chosen. A total of 34 DTMs were created for comparison from the three independent hydrographic data sets.

RESULTS AND DISCUSSION

Evaluation of the hydrographic survey technique

The maximum storage volume was calculated as 131,968 m^3 (~ 132 ML) from measurements using the traditional RTK GPS land based technique. Differences in the maximum storage volumes measured using the hydrographic and land survey techniques ranged from 0.1% for the high intensity (10 m x 5 m) hydrographic survey to 1.0-1.4% for the lower intensity (i.e. 20 m x 10 m and 20 m x 20 m) hydrographic surveys (Table 1).

INSERT TABLE 1 NEAR HERE

The point measurements of the storage surfaces obtained with the lead line were used to evaluate the accuracy and precision of the different survey methods (Table 2). The lead line drop measurements were highly correlated with both the land based and hydrographic DTMs. The average difference in point heights were similar (~0.01-0.03 m) between the land based and high intensity hydrographic survey. However, increasing the transect and point spacings of the hydrographic survey increased the average point height difference to between 0.06 and 0.11 m.

INSERT TABLE 2 NEAR HERE

As expected, the precision of the measurements was higher in the land based survey than the hydrographic surveys (Table 2). The precision was found to decrease in the hydrographic surveys with increasing transect and point spacing. Even though the precision estimate for the hydrographic measurements are greater than 0.2 m, the average height difference was less than 0.11 m providing confidence in the depth sounder calibration process. This suggests that under and over-estimates on individual point measurement heights tend to average out, minimising the error in both the DTM surfaces generated and the volume measurements.

The absolute errors in the stored water volumes measured using the hydrographic surveys are small and decrease with water level (Figure 4a). However, where the water level is used as a measure of the water volume remaining in the storage, the error in the measured water volume should more appropriately be expressed as a percentage of the residual water volume. When expressed as a proportion of the residual water volume, the volumetric accuracy of the hydrographic survey was found to decrease as the water level in the storage decreased (Figure 4b). Errors of greater than 5% of the residual volume were found for the high intensity hydrographic survey when the water depth was less than 1.5 m. Similarly, errors greater than 5% of the residual volume were obtained using the lower intensity hydrographic surveys where the water depth was less than 2 m.

INSERT FIGURE 4 NEAR HERE

Effect of sampling point density on DTM accuracy

Decreasing the sampling point density was found to considerably reduce the accuracy of the volumetric measure (Figure 5). Increases in both the point and transect spacing were found to increase the measurement error (Figure 6). However, the effect of increasing the transect spacing was greatest with transect spacings of 30 to 40 m resulting in errors greater than 3% irrespective of point spacing.

INSERT FIGURE 5 NEAR HERE

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The high degree of scatter found in the volumetric error (Figure 5) with increasing point and transect spacing is most likely due to differences in interpolation associated with the DTM generation. The larger impact of transect spacing on volumetric error (Figure 6) is caused by not properly defining the bottom features even though a large number of points were used and the grid area between points was relatively small. For example, measuring points at 5 metre spacing along transects that are 40 metres apart will give the impression there are sufficient points to accurately define the underwater surface, but substantial surface features may be missed because of the large transect spacing (Figure 7). To minimise these difficulties, the ratio of transect to point spacing should be as close as possible to one (Clark 1972, pp. 291).

INSERT FIGURE 7 NEAR HERE

The DTM generation software used in this study fitted planar surfaces between the measured points. However, as the dam surfaces are normally non-linear, fitting planar surfaces between measured points will typically lead to the storage volumes being under-estimated, with the error increasing as point and transect spacings increase (e.g. Table 1; Figure 5). The surface estimation error is a function of the storage surface evenness (see Clark, 1972). For the measured storage, a grid area of <200 m^2/measured point was required to obtained an error of <1% (Figure 5).

A substantial proportion of the volume error was due to inadequately defining the point of inflection (change of grade) between the bank and floor of the storage (Figure 8). Hence, for this small storage, the accuracy of the storage volume was heavily influenced by the location and number of point measurements near the inflection point. A volume error of 1.73 m^3 per linear metre of bank was measured at the ends of the 20 metre transects. However, a volume error of 6.70 m^3 per linear metre of bank was found for the banks running parallel to the transects. This suggests that the volume error may be reduced by more accurately identifying the inflection point between the storage walls and floor. This could be achieved by measuring additional transects, with closer point spacings, taken at right angles to the main transects between the water's edge and start of the storage floor. Alternatively, it may be more time and cost effective to navigate around the inside circumference of the dam in a zigzag pattern between the water line and where the floor flattens out.

As the storage size increases, the effect of inadequately defining the inflection point on the overall volume error decreases (Figure 9). For a 450 ML storage with a generally flat bottom (i.e. 300 m x 300 m x 5 m deep), the use of a zigzag pattern around the inside of the storage circumference would increase the accuracy by 0.66%. However, for an 1800 ML storage (i.e. 600 m x 600 m x 5 m deep), it would increase the accuracy by 0.33%. This is a major difference between how ring tanks of this shape, with a strong inflection point, should be measured compared with the method described by Nazaretian (2003) for comparatively large water storages that don't have a strong inflection point.

INSERT FIGURE 8 NEAR HERE

INSERT FIGURE 9 NEAR HERE

The error in the storage floor measurement was found to increase as the area per measurement point increased (Table 3). As the size of the storage increases, the effect of the error associated with the identification of the inflection point between the wall and storage floor reduces (Figure 9) and the dominant factor contributing to the volumetric error is measurement point density and how accurately the storage floor is measured. Hence, the error in the storage volume measurement should decrease and become asymptotic with the storage floor error as storage size increases.

INSERT TABLE 3 NEAR HERE

Kriging software (e.g. Collier et al., 2003; Cressie, 1991), which fits non-linear surfaces to the point measurements, could be used to improve the DTM generation and potentially reduce surface estimation errors. While the volumetric errors obtained for the measured storage were small (typically <1%), this error would also be expected to increase with increasing unevenness of storage surfaces and decreasing point density. However, further research is required to determine the marginal benefit that would be obtained from using this software under various storage and measurement conditions.

Recommendations for hydrographic measurements

Based on the data obtained from the measured storage and assuming a similar evenness of storage surfaces, it would seem reasonable to make the following recommendations regarding the intensity of hydrographic measurements. Where a measurement accuracy of less than 1% is required, storages smaller than 350 ML in size should be surveyed with a 10 x 20 m grid and navigate a zigzag pattern around the inside of the banks. Storages between 350 and 1800 ML in size will require either a 10 x 20 m grid survey without special bank treatment or could utilise a 20 x 40 m grid if a zigzag pattern is used around the inside of the banks. Storages greater than 1800 ML in size can be surveyed using a 20 x 40 m grid without any special bank treatment. For these larger storages, increasing the surveying grid to 40 x 80 m may reduce the accuracy to approximately 1.3 %. However, as the magnitude of the error, and hence the selection of an appropriate point density, is a function of the storage floor evenness, further measurements on additional storages need to be undertaken to confirm the validity of these recommendations.

CONCLUSION

The low cost hydrographic technique described in this study has been found to be an appropriate technique to measure on-farm water storage volumes. While the precision of the hydrographic measurements were lower than the traditional land based survey, average differences in point heights were similar between the land based and high intensity hydrographic survey. Both accuracy and precision increased with increasing point density. Point and transect spacings should be chosen with regard to the size of the storage and the unevenness of the storage surfaces. For comparatively small storages, accuracy was principally influenced by the ability to identify the point of inflection between the storage banks and floor. However, on larger storages, errors due to the identification of the inflection point are comparatively minor and the principal factor influencing accuracy is the unevenness of the storage floor.

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TABLES

Table 1. Storage volumes calculated using the hydrographic measurements taken at various transect and point spacings.

Transect spacing (m)	Point spacing (m)	Maximum storage volume (m^3)	Difference in maximum volume compared with land based survey	
			(m^3)	(%)
10	5	132144	176	0.1%
20	10	130058	-1910	- 1.4%
20	20	130615	-1353	- 1.0%

Table 2. Summary of point accuracy and precision as measured using lead line drops

Survey method	Transect width (m)	Point spacing (m)	Correlation coefficient [a]	Average difference of individual point measurement heights (m)	Root mean square [b] (m)
Land based				-0.026	0.103
Hydrographic	10	5	0.94	0.009	0.236
	20	10	0.85	0.107	0.390
	20	20	0.84	0.064	0.389

[a] r^2 value for correlation between the land based and hydrographic surveys
[b] precision estimate

Table 3. Increasing the area per measured point across the storage floor increases the volume error

Point spacing (m)	Area per measured point (m^2 / point)	Absolute volume error (m^3 / 100 m^2 floor area)	Absolute volume error [1] (%)
10 x 20	200	1.75	0.35
20 x 40	800	4.37	0.87
40 x 80	3200	6.18	1.24

[1] expressed as a percentage where storage is 5 m deep

FIGURES

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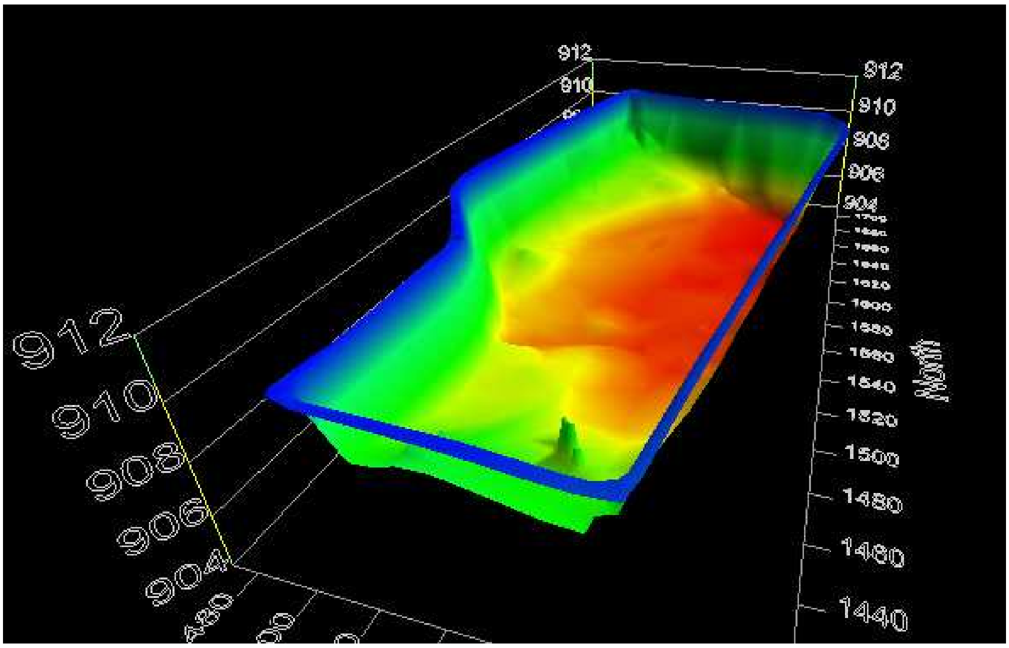

Figure 1. Digital terrain model of the 132 ML Stanthorpe storage
(units are in metres from local origin)

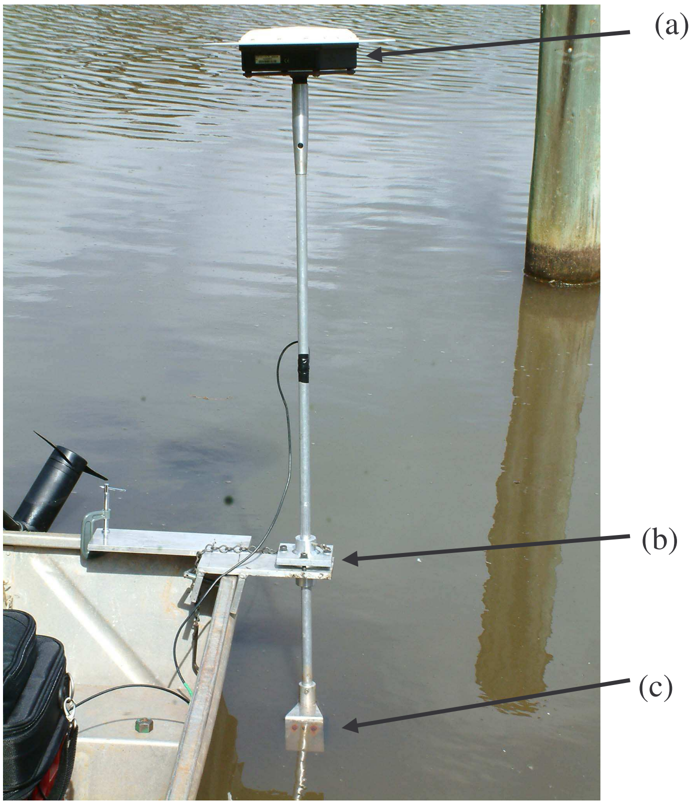

Figure 2. Sensor configuration showing (a) GPS antenna, (b) tilt adjustable ball joint and (c) depth sounder

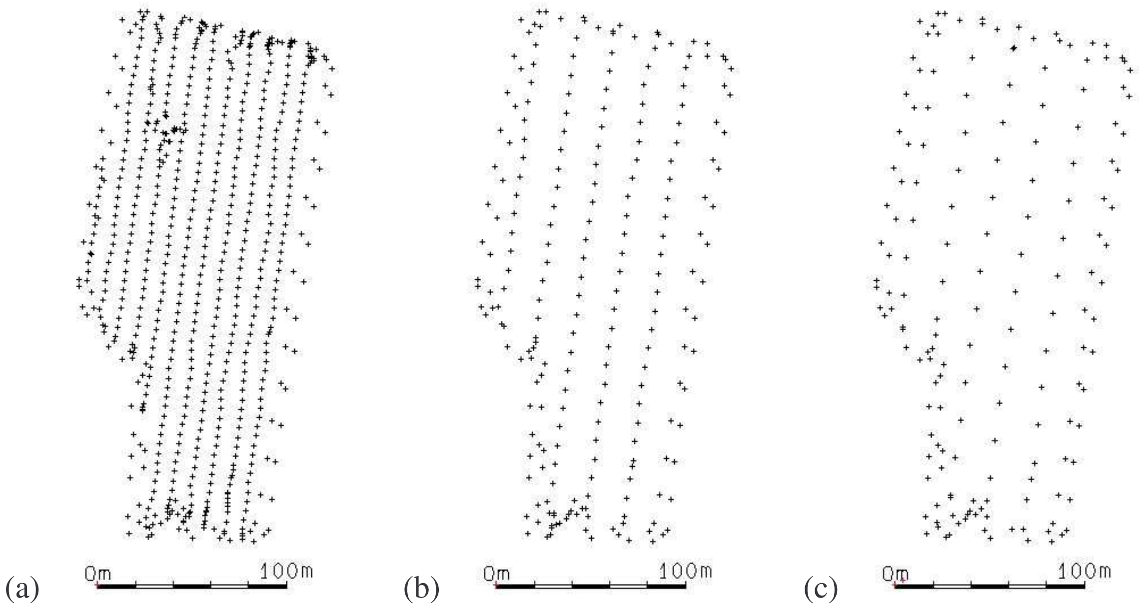

Figure 3. Parallel transects and fixed point distances for (a) 10 x 5 m, (b) 20 x 10 m and (c) 20 x 20 m hydrographic DTMs
(units are in metres)

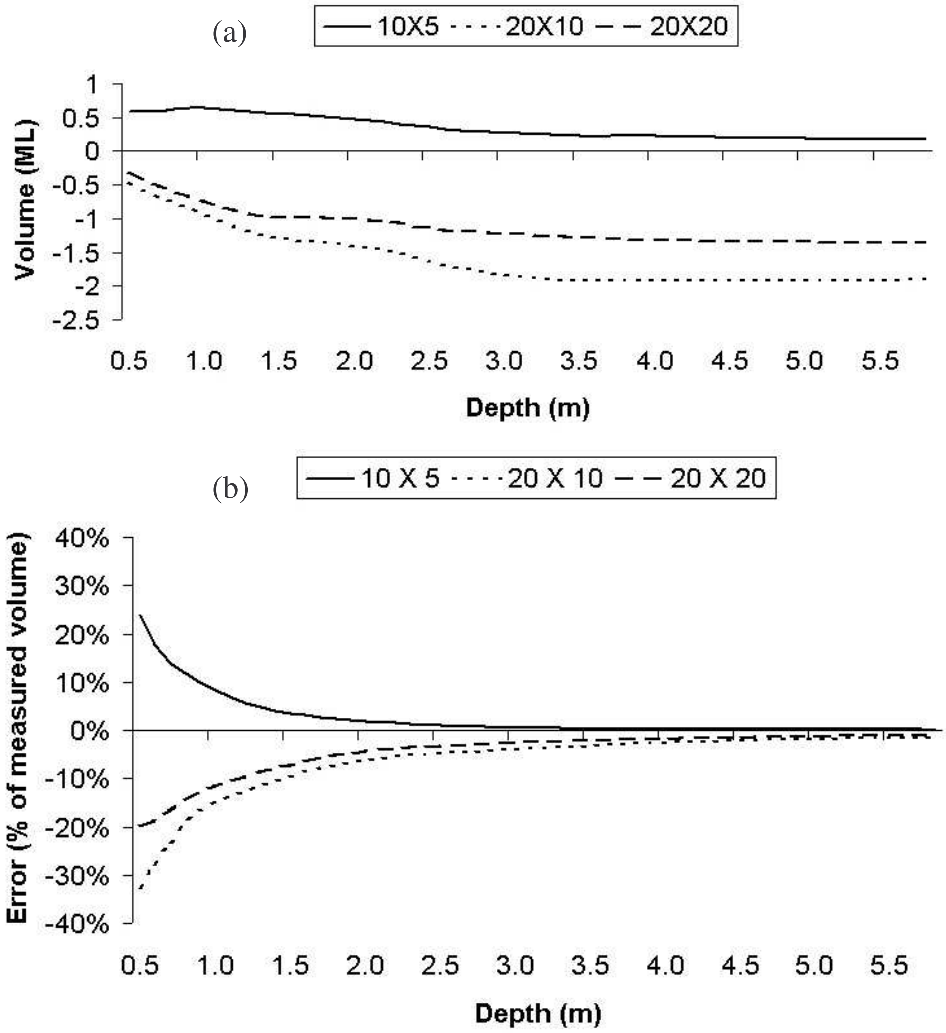

Figure 4. Error in measured volume obtained using the hydrographic survey expressed (a) as a volume and (b) as a percentage of the residual volume of water for each depth

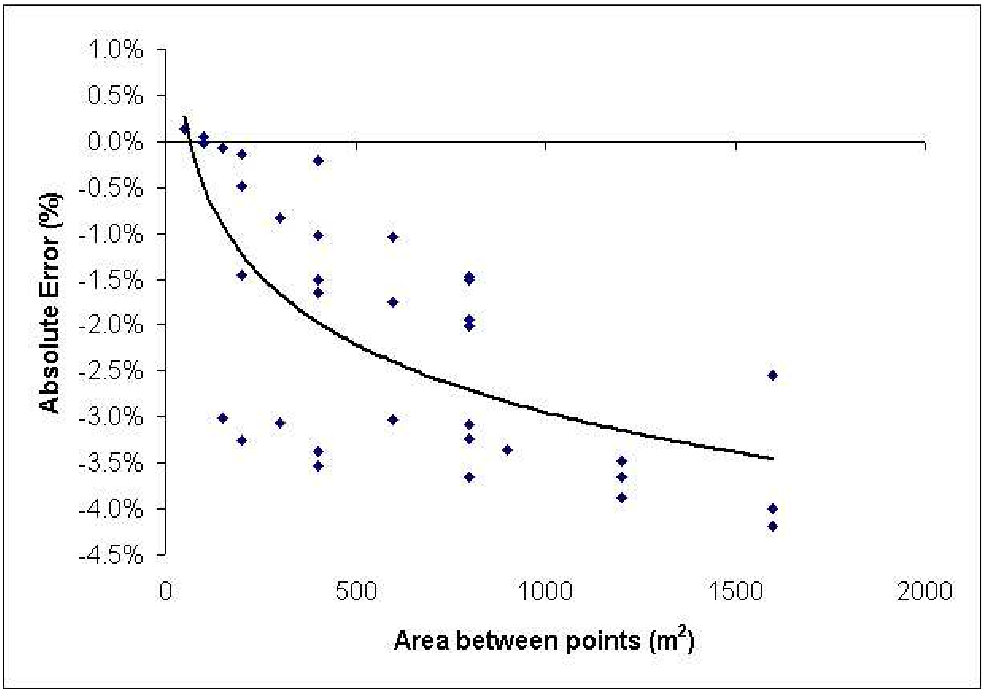

Figure 5. Increasing the area between points increases the error in the volumetric measure

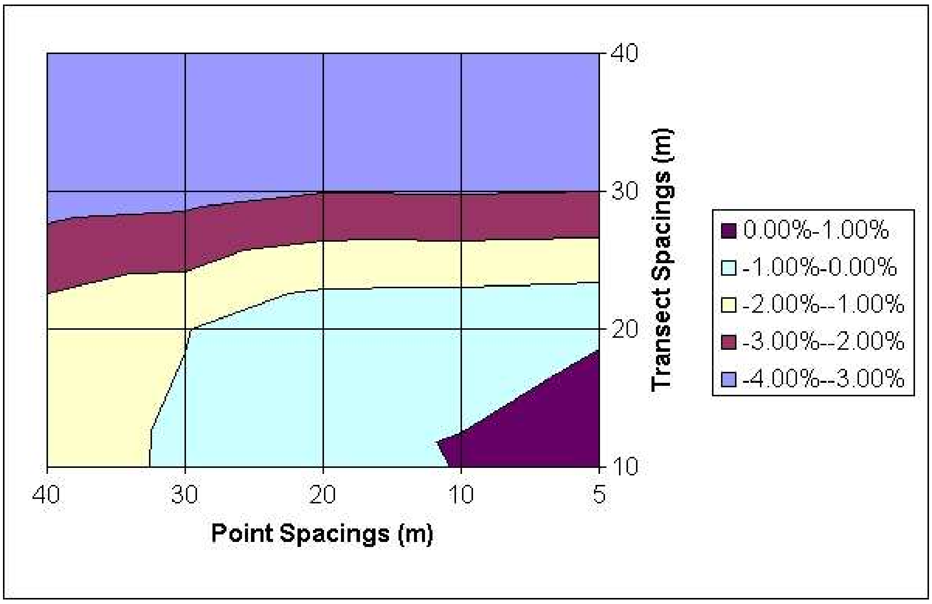

Figure 6. Effect of transect and point spacing on error in storage volume measurement

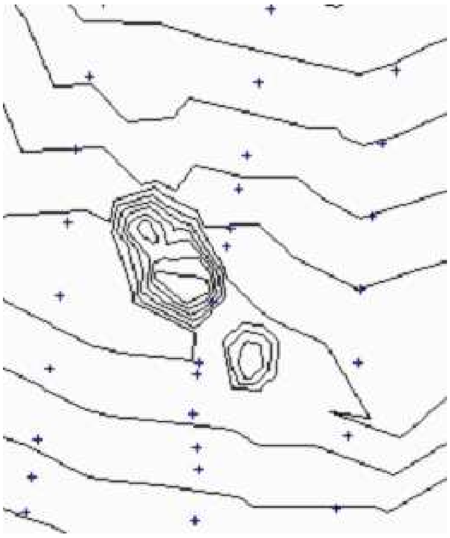

Figure 7. Wide transect spacings can result in missed surface features

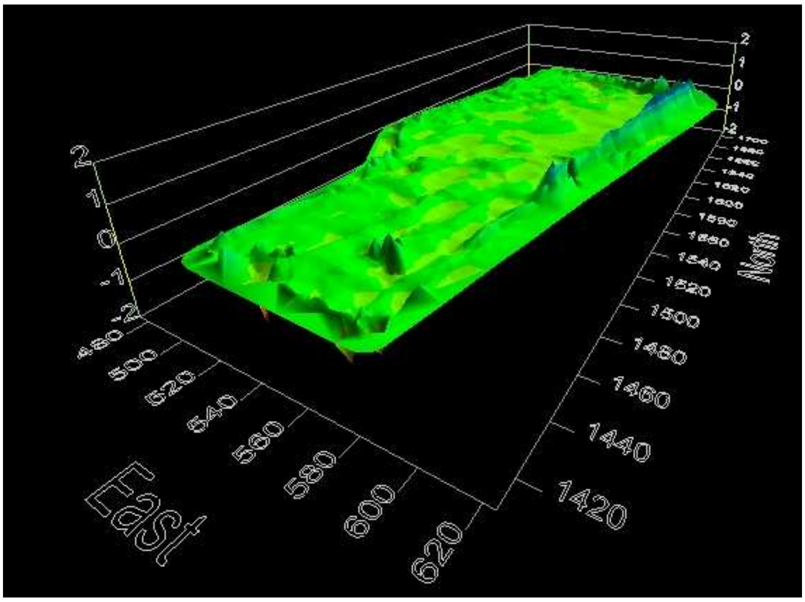

Figure 8. Isopach layer showing the difference between the digital terrain models generated using the conventional land and 10 x 5 m hydrographic survey
(units are in metres from local origin)

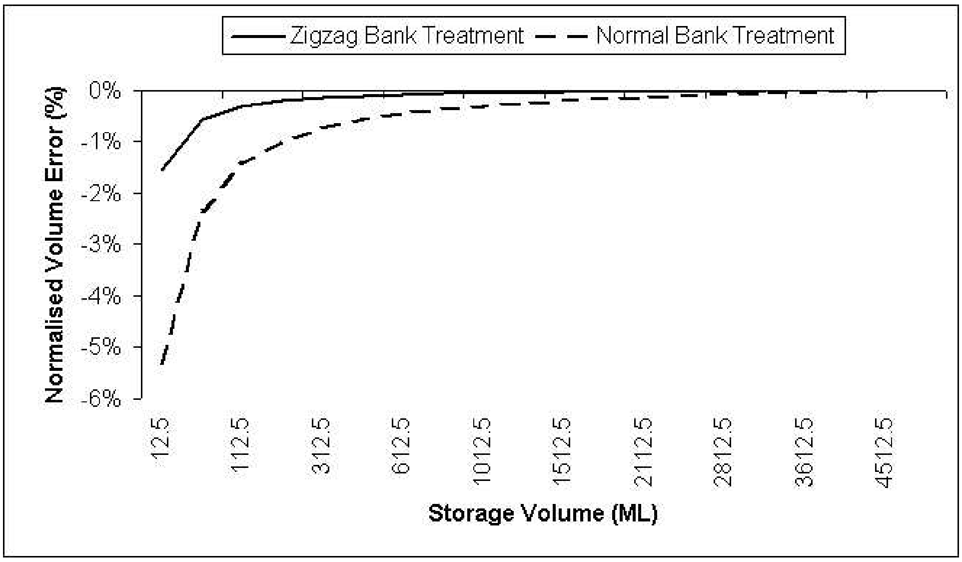

Figure 9. Effect of improving the delineation of the inflection point between the storage walls and floor (40 x 80 m DTM)