RECOMMENDED GEOMORPHIC CHANGE DETECTION PROCEDURES FOR REPEAT TLS SURVEYS FROM HELLS CANYON, IDAHO

REPORT TO IDAHO POWER COMPANY

Prepared by:

RYAN J. LEARY, Research Assistant

JAMES W. HENSLEIGH, Research Assistant

DR. JOSEPH M. WHEATON, Assistant Professor

KENNY D. DEMEURICHY, Surveyor and Terrestrial Laser Scanning Analyst

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Ecogeomorphology & Topographic Analysis Lab

Watershed Sciences Department Utah State University 5210 Old Main Hill Logan, UT 84322-5310



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EXECUTIVE SUMMARY

The primary purpose of this report is to recommend methods that Idaho Power Company (IPC) could employ to undertake a robust geomorphic change detection analysis and subsequent interpretation with their growing library of repeat terrestrial laser scanning (TLS) of sand and gravel bars in Hells Canyon. The recommended methods address field data acquisition, data post processing, and change detection using post processed data. The workflows presented in this report are intended to leverage cutting edge research and facilitate accurate geomorphic change detection by adhering to best practices in the fields of topographic surveying and analysis.

Central to the report are step-by-step instructions of tractable and defensible techniques for undertaking change detection analyses with TLS data. There are an array of choices in the analysis available to IPC, and here clear guidelines are provided for navigating those decisions, and where appropriate general recommendations are suggested. The accuracy of a geomorphic change detection study is limited by the uncertainty involved in the surveying methods. Missteps in field data acquisition greatly limit the potential accuracy of a geomorphic change study as well as the ability to make robust and educated interpretations of the final results. A review of IPC's TLS field data acquisition revealed satisfactory practices concerning the accuracy of measurements however there are three main issues that could potentially hinder subsequent analysis: inconsistent augmentation of total station (TS) surveyed data, inconsistent use of coordinate systems and survey extents, and lack of data in wadeable shallow water areas of the sand/gravel bars. A survey strategy and associated techniques are presented in this report to overcome these issues.

TLS data post processing and preparation is time consuming and if done incorrectly or in the wrong order (e.g. in the wrong coordinate system), can be a complete waste of effort. The current practice of not surveying in and or registering data into the final coordinate system the analysis shall be done in (i.e. Idaho Power Coordinate System) before cleaning the data has resulted in a lot of post-processing by IPC contractors that cannot be used in subsequent analyses. Before any IPC employee or outside contractor begins cleaning and post-processing of the co-registered scan data, it should be first transformed into the Idaho Power Coordinate System. For all future TLS surveys, all ground control coordinates used in the field should be established in Idaho Power Coordinate System to eliminate the need for later transformation of the data. The workflow presented addresses this issue with clear instructions as to how to avoid this pitfall.

The large datasets produced by TLS surveys are cumbersome for most GIS and CAD applications and present serious post-processing challenges. To get around this, point clouds are typically decimated to smaller datasets that are orders of magnitude smaller and allow modeling with simple high resolution raster digital elevation models (DEMs). The freely available point cloud processing software, PC-Tools, is recommended as a highly efficient tool specifically designed for the task of decimating large point clouds and producing point clouds of manageable size for popular GIS software. Included in the output of this software is a summary of block-centered cell-statistics, which is an integral product for developing both roughness and uncertainty models necessary for later steps of geomorphic change detection.

The development of an uncertainty model for each DEM is the cornerstone of a defensible and robust change detection study by providing a means to distinguish real geomorphic change from uncertainty due to surveying noise and post processing relics and errors. Geomorphic Change Detection Software 5 (GCD 5) was specifically designed to streamline such analyses. The methods to implement three distinct uncertainty models, spanning a range of complexities, are explicitly detailed in this report. Outputs from this software include tabular and

graphical presentations of areal and volumetric totals of erosion, deposition and uncertainty. The additional functionality of budget segregation gives the user the ability to compartmentalize geomorphic change by defined units which is a powerful tool in pinpointing the kinematics of change while providing insight into the mechanisms influencing erosion and deposition.

The recommendations of this report are based in consistent and defensible techniques from the fields of topographic analysis and surveying. The basic principle throughout is keeping the analysis as conservative and simple as possible, and bolting on complexity only as is necessitated by the inadequacy of the simpler analysis to resolve changes of interest. The principles behind the generic methods outlined in this report should be defensible for many years. However, the detailed step-by-step methods will become slightly outdated over time as the software to do these analyses evolves and improves. However, it is likely that those software improvements will only act to simplify and streamline the workflows advocated here. In the meantime, this report provides IPC employees and contractors with explicit instructions for correcting the identified shortcomings in field data acquisition, data post processing, and change detection facets of the Hells Canyon monitoring project.

BACKGROUND & PURPOSE

Idaho Power Company (IPC) has been undertaking repeat topographic surveys of numerous sand bars and gravel bars in the Hells Canyon section of the Snake River for the past seven years. As the bars are important ecologically and recreationally, IPC is interested in how these sediment deposits change and evolve through time. The surveys IPC undertakes of these bars are generally annual repeat surveys taken during low flows in the autumn. The primary method IPC has employed to capture the status of these bars has been through ground based surveys using terrestrial laser scanning (TLS), also known as ground based LiDaR. Over the past decade, TLS has emerged as an exciting frontier in monitoring earth surface processes, because of the extremely high resolution of the scan data (e.g. point spacing of 1-10 mm) and its ability to resolve topographic, roughness and vegetative features previously impractical to measure over anything but small plot scales (Milan *et al.*, 2007; Brasington *et al.*, 2008; Heritage and Large, 2009; Hodge *et al.*, 2009). With this TLS data in hand from different snapshots in time, the problem IPC is faced with is a geomorphic change detection problem. The primary questions that emerge are:

- a) How should IPC distinguish real topographic changes from noise?
- b) How should IPC interpret the detectable topographic changes, geomorphically?
- c) Are there any changes to IPC's survey acquisition methods, which might facilitate addressing a) & b) with greater ease or more confidence?

The Ecogeomorphology and Topographic Analysis Lab (ET-AL) and Dr. Wheaton have been working since 2002 on the problem of geomorphic change detection and have been working with ground-based LiDaR since 2005. ET-AL has developed a variety of innovative geomorphic change detection techniques (Wheaton, 2008; Wheaton *et al.*, 2010), which are encompassed in their Geomorphic Change Detection Software (GCD 5) and PC-Tools (Rychkov *et al.*, 2010). As the practice of doing change detection in fluvial environments is so new, 'standards of practice' do not yet exist (Heritage and Hetherington, 2007). However, IPC can help to set the standard of practice through undertaking consistent and defensible change detection analyses advocated here.

The primary purpose of this report is to recommend methods that IPC could employ to undertake a robust geomorphic change detection analysis and subsequent interpretation with their growing library of repeat TLS surveys of bars. We will use a subset of IPC TLS data from two of their study bars to illustrate application of the recommended methods. The recommended methods will be explained in this report in terms of a workflow, which IPC staff or its contractors can follow to process both the existing datasets and future datasets as they are collected and ingested into the IPC library of repeat surveys of sand and gravel bars.

Although the methodological development in this field is an area of active cutting edge research that is continuing to evolve, there are some basic change detection principles that IPC should adhere to and for which robust and defensible methods are demonstrated herein. In general, IPC should seek to develop error models for all their topographic surfaces, which are spatially variable, and which err on the side of being conservative. The error models advocated in this report are tractable to derive with existing data, but are not as sophisticated as is currently possible. As a basic principle, investment in more sophisticated error models should only be undertaken when simpler methods are shown to be inadequate at capturing changes of interest.

It should be cautioned that although the methods of geomorphic change detection can be used to produce reliable estimates of measurable net change, there will still generally remain some fraction of changes that are undetectable. Moreover, while the geomorphic process interpretation of said changes is generally reliable and repeatable, explaining the causes of those changes requires additional and complimentary methods. Geomorphic

change detection captures the kinematics of change, leaving the mechanics and precise causes of those changes to logical inference and/or other lines of inquiry.

HELLS CANYON STUDY SITES

Hells Canyon is a roughly 70 mile stretch of the Snake River situated along the western Idaho and eastern Oregon borders (Figure 1). The Snake River is a major tributary to the Columbia River, with its headwaters in Yellowstone and Grand Teton National Parks. The Snake flows out of the Rockies and extends westerly across the Snake Plane of Idaho until it starts heading north and forms part of the boundary between Idaho and Oregon. The Hells Canyon Hydroelectric Complex is located on the Snake River in the southern portion of Hells Canyon and includes three reservoirs: Brownlee, Oxbow, and Hells Canyon. Hells Canyon Dam is the furthest downstream and is at River Mile (RM) 247 (river miles are upstream from the Columbia River).

Hells Canyon is the deepest canyon in North America and home to IPC's largest hydroelectric generating complex, the Hells Canyon Complex (HCC) (Parkinson *et al.*, 2002). The HCC includes the Brownlee, Oxbow, and Hells Canyon dams, reservoirs, and power plants. Operations of the three projects of the complex are closely coordinated to generate electricity and to serve many other public purposes (Holthuijzen, 2001). IPC operates the complex to comply with the FERC license, as well as to accommodate other concerns, such as recreational use, environmental conditions and voluntary arrangements (Holthuijzen, 2001). Among these arrangements are the 1980 Hells Canyon Settlement Agreement, the *Fall Chinook Recovery Plan* adopted in 1991, and, between 1995 and 2001, the cooperative arrangement that IPC had with federal interests in implementing portions of the Federal Columbia River Power System (FCRPS) biological opinion flow augmentation, which is intended to avoid jeopardy of the FCRPS operations.

Brownlee Reservoir is the only one of the three HCC facilities—and IPC's only project—with significant storage. It has 101 vertical feet of active storage capacity, which equals approximately 1 million acre-feet of water. On the other hand, Oxbow and Hells Canyon reservoirs have significantly smaller active storage capacities—approximately 0.5 and 1.0% of Brownlee Reservoir's volume, respectively. Brownlee Dam's hydraulic capacity is also the largest of the three projects. Its powerhouse capacity is approximately 35,000 cubic feet per second (cfs), while the Oxbow and Hells Canyon powerhouses have hydraulic capacities of 28,000 and 30,500 cfs, respectively. Target elevations for Brownlee Reservoir define the flow through the HCC. However, when flows exceed powerhouse capacity for any of the projects, water is released over the spillways at those projects. When flows through the HCC are below hydraulic capacity, all three projects operate closely together to re-regulate flows through the Oxbow and Hells Canyon projects so that they remain within the 1-foot per hour ramp rate requirement (measured at Johnson Bar below Hells Canyon Dam) and meet daily peak load demands. In addition to maintaining the ramp rate, IPC maintains minimum flow rates in the Snake River downstream of Hells Canyon Dam. These minimum flow rates are for navigation purposes and IPC's compliance with article 43 of the existing license. Neither the Brownlee Project nor the Oxbow Project has a minimum flow requirement below its powerhouse. However, because of the Oxbow Project's unique configuration, a flow of 100 cfs is maintained through the bypassed reach of the Snake River below the dam (a segment called the Oxbow Bypass).

Within Hells Canyon, IPC have a total of 18 sand or gravel bars that have been surveyed using terrestrial laser scanning (TLS) at least once (Table 1). The study area itself is located downstream from Hells Canyon Dam (RM 247) and upstream from the confluence with the Salmon River (RM 188) between RM 192 and RM 245 (Figure 1 and Table 1). Of these 18 sites, six sites have been sampled more than once with five sampled each year from 2005 through 2010 (Table 1). Given the scope and purpose of this report, only two sites were chosen for an in-depth analysis. In consultation with IPC, China Bar and Pine Bar were chosen as the focus of this report. Two factors that

determined the selection of these two bars were: 1) both had six years of TLS data, and 2) one site is a sand bar, China Bar, and one site is a gravel bar, Pine Bar, allowing for a comparison of methodology and results between the bar types.

China Bar is located at RM 192.3 on the Oregon side of the Snake River (Figure 2). China Bar is a popular sandbar campsite for rafters and occurs just upstream of the confluences with the Imnaha (RM 191.6) and Salmon Rivers (RM 188.3). The upstream boundary is composed of a debris fan, while the downstream boundary is a bedrock outcrop (Parkinson *et al.*, 2002). China Bar is adjacent to a high terrace that delineates the southeast boundary of the study area, while the river forms the northwest boundary. The bar is composed of fine to coarse sand and relatively free of gravels (Parkinson *et al.*, 2002). TLS data for China Bar started in the autumn of 2005, and has repeated each year since (Table 1).

Pine Bar is located on the Idaho side of the Snake River at RM 227.5 (Figure 3). Pine Bar has been documented as a rearing area for fall chinook salmon, supporting high numbers of juvenile white sturgeon, and supporting adult white sturgeon (Chandler *et al.* 2001). Other fish species that have been documented using this site include subadult/adult redband and bull trout (Chandler *et al.* 2001). Pine Bar has also been documented as a popular boat landing (Parkinson *et al.*, 2002). The site has an average width of 139 m at a flow of 30 kcfs (Chandler *et al.* 2001). The channel in this section of river is confined by a mixture of bedrock and alluvial terraces and characterized as having moderate sinuosity (Miller *et al.* 2002). The bar is protected by a bedrock outcrop on the upstream end, with the downstream end fading into a debris fan (Parkinson *et al.*, 2002). The east side of the bar (bank side) is composed of a landslide that transitions into the high sand terrace (Parkinson *et al.*, 2002). Two house-size rocks (bedrock outcrops) that are approximately 20 by 14m (66 by 46ft) and 14 by 8m (46 by 26ft) in size are located in the center of the river channel approximately across from the bar (Parkinson *et al.*, 2002). At least 3m (11ft) of the largest rock is exposed under normal operational flows. This pair of rocks strongly influences flow patterns in this reach of the river (Parkinson *et al.*, 2002).

Bar Name	ID / OR	RM	2005	2006	2007	2008	2009	2010
Brush Creek Mouth	ID	244.7			Х			
Brush Creek Spawning	ID	244.6			Х			
China	OR	192.3	Х	Х	Х	Х	Х	Х
Coral Creek	ID	217.3		Х				
Durham	ID	217.6	Х	Х				
Fish Trap	OR	216.4	Х	Х	X	X	X	Х
Half Moon	OR	221.4		Х				
High Range	ID	206.4		Х				
Hominy	OR	222.9			Х			
Little	OR	224.9		Х				
Lower Dug	ID	196.0			Х			
Lower Pleasant Valley	OR	213.9		Х				
Pine	ID	227.5	Х	Х	Х	Х	Х	Х
Pittsburg	ID	214.7		Х				
Quartz Creek	OR	226.5		Х				
Salt Creek	OR	222.4	Х	Х	Х	Х	Х	Х
Suicide Point	ID	222.7			Х			
Tin Shed	OR	215.7	Х	Х	Х	Х	Х	Х

Table 1 - Sites that have TLS data for a particular year are marked with an 'X'. If the bar is on river right the site is located within Idaho (ID). If the bar is on river left the site is located in Oregon (OR).

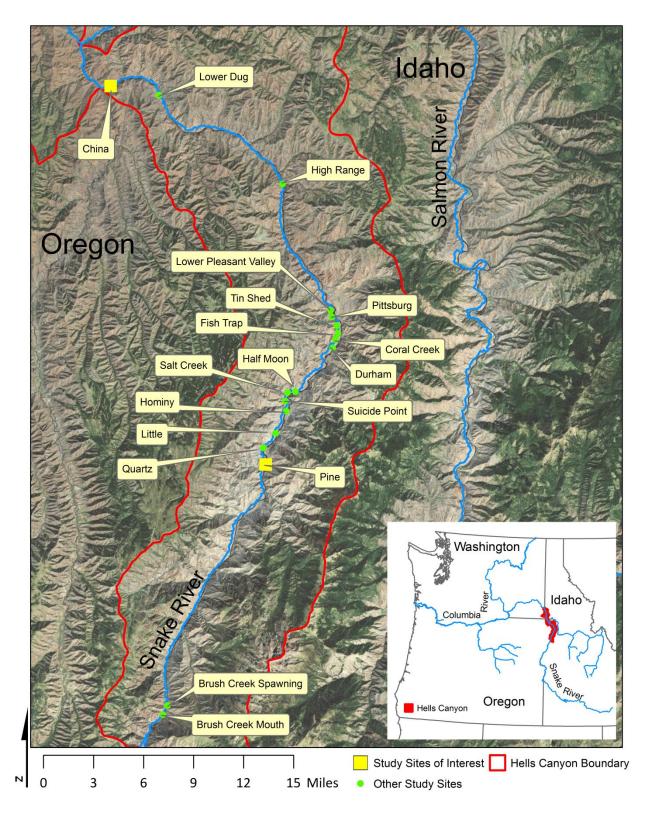


Figure 1 - Location of Idaho Power Company study locations along the Snake River within Hells Canyon.

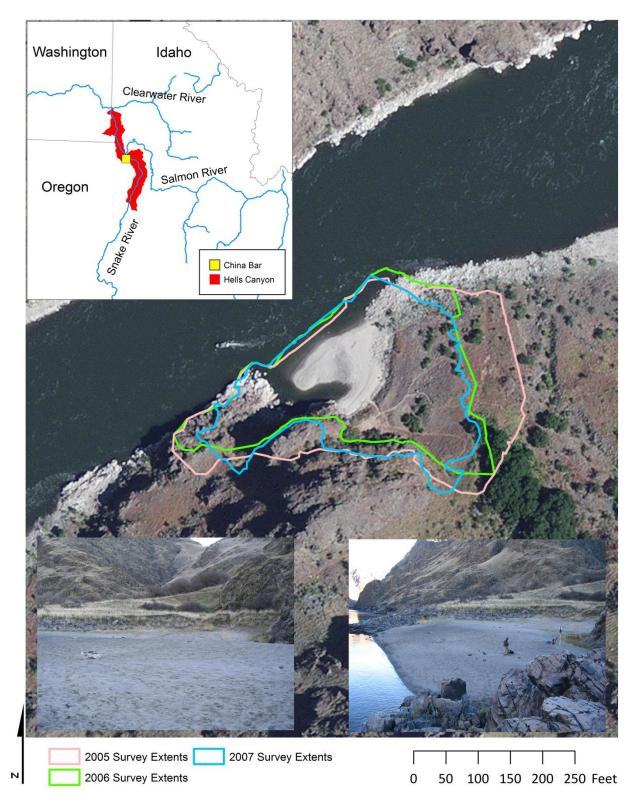


Figure 2 - China Bar study location, RM 192.3, along the Snake River within Hells Canyon in Oregon.

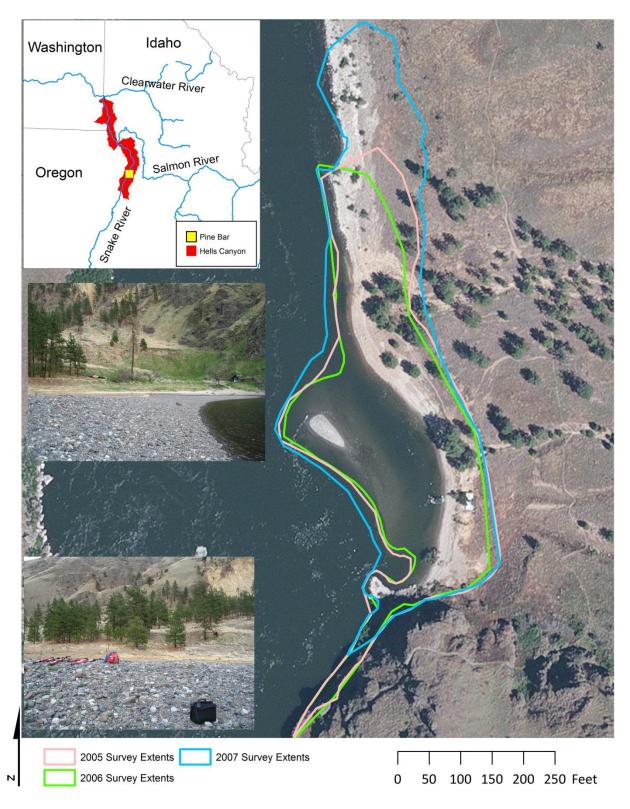


Figure 3 - Pine Bar study location, RM 227.5, along the Snake River within Hells Canyon in Idaho.

RECOMMENDED WORKFLOW

The focus of this report is to describe methodology to take topographic terrestrial laser scanning (TLS) and total station (TS) data and produce DEMs of Difference (DoDs), providing IPC a way to analyze geomorphic changes in sand/gravel bars along the Snake River in Hells Canyon. Using Leica's Cyclone software, TLS data was collected in the field and then edited in an office to produce *.pts files. The *.pts files are processed through PC-Tools to produce files which are manageable for AcrGIS. Using the decimated files from PC-Tools, a variety of surfaces are created in ArcGIS. Geomorphic Change Detection software is then used to create DoDs using surfaces created in ArcGIS.

The topographic data used in the data flow process consists of a combination of TLS and TS data. All data have been registered in the same coordinate system, Idaho Power Coordinate System. All post processing of TLS data was done in Cyclone 7.1 since TLS data was collected using Cyclone software. First, all scans in each reach were coregistered to a common coordinate system and then transformed onto the same coordinate system as the control and TS data. Next, undesirable points in the scan data was manually filtered including boats, people, survey equipment, vegetation, and other features that do not represent the landscape. To facilitate use of the point cloud data in other point cloud software, the point clouds were exported for each reach by year into a *.pts format, which is a generic ASCII point cloud format.

The *.pts versions of the processed point clouds are appropriate for point cloud software, but at file sizes ranging from 1 to 4 GB, they cannot be practically used in most GIS applications. Most CAD and GIS programs are not designed to handle the high-density point clouds produced by TLS data. Although ArcGIS now has a multi-point feature model that can be used to build terrains from large point clouds, functionality is limited as compared to regular point feature classes and regular TIN construction. It is thus desirable to decimate the dataset down to file sizes more manageable for GIS applications. A point-cloud decimation algorithm called PC-Tools (Rychkov et al., 2010) was used to reduce the point clouds down to 1 point per 1ft x 1ft cell. Given the variability of the sand and gravel bars that IPC is likely to work with we also show how a variable decimation process can be used to differentiate between areas within sand or gravel bars and areas within vegetated and uneven, rocky areas. We chose to use 1 point per 1ft x 1ft cell for sand and gravel areas and 1 point per 5ft x 5ft cell for areas outside these areas. 1 point per 1ft x 1ft cell and 5ft x 5ft cell are data densities that standard GIS packages can handle for digital terrain and elevation modeling. The decimation algorithm in PC-Tools produces a variety of outputs:

- At the center of each cell: minimum elevation, maximum elevation, mean elevation, elevation range, standard deviation of elevation, detrended (for local slope) standard deviation of elevation, detrended mean elevation, and a point count (i.e. point density).
- It also exports the coordinate value (x,y,z) of the absolute minimum elevation point and absolute maximum elevation point.

Each of these outputs can be used to produce surface models. For example, the elevation range is a good indication of vegetation heights, the max is a good model of the tree canopy and can be used to make a terrain model (analogous to first return from airborne LiDaR), and the minimum is a reasonable approximation of a bare earth topography. Raster surfaces were produced using minimum elevation, detrended standard deviation, and point count.

Using minimum elevation, bare earth surface models were made in ArcGIS 10. Triangulated Irregular Networks (TINs) were created from TS and decimated TLS data, edited, and used to create Digital Elevation Models (DEMs). DEMs were used to produce slope rasters. Point density rasters were produced using point count as the z-value

and surface roughness rasters were produced using detrended standard deviation as the z-value. Slope, point density, and roughness rasters were used in a Fuzzy Inference System (FIS) to determine the error associated with each cell in a DEM surface. Using DEM surfaces and the error associated with each cell, Geomorphic Change Detection 5.0 software was used to evaluate geomorphic changes at China Bar and Pine Bar.

FIELD DATA ACQUISITION

The quality and quantity of data collected in the field effects the data processing procedures and can influence the accuracy of the results. Survey extents also play an important role in producing reliable, accurate results. To maximize the amount of data collected at each sand/gravel bar it is recommended to continue field data collection during low flow. Data collection at low flow ensures the greatest extent of each sand/gravel bar is captured using the terrestrial laser scanner, providing a high density of data points. Also, it is more efficient to get high density data with a terrestrial laser scanner than a total station.

TLS data collected at China Bar and Pine Bar by IPC contractors has been sufficient; however, in our opinion the inconsistently augmented TS data is insufficient and could greatly improve. We recommend collecting more TS data and also to collect breaklines to distinguish breaks in slope. If vegetated and rocky areas are of interest for calculating geomorphic change detection (GCD) it is recommended to not rely on TLS data but rather supplement TLS data with TS data to ensure these areas are well represented within a point cloud. When increasingly vegetated surfaces are included in the survey extents, it is often more accurate and time efficient to simply survey these vegetated areas with a TS.

Another area of improvement for TS data collection is the collection of data where water covers the bar surface. Eddy complexes extend offshore into the water and these dynamic areas are continually changing. To create an accurate budget of sediment in storage in these eddies, the offshore areas need to be surveyed as well (Hazel et al., 2006; Hazel et al., 2010). In these areas, more data of offshore eddy areas will produce better, more representative results. Also, at Pine Bar there were times when water covered the bar surface, creating a gap in TLS data. These areas were either neglected or TS data was collected so sparsely as to render them useless for sediment budgeting purposes (Figure 4). Although these areas may create difficulties in data collection due to water depth and/or current, it is important that these areas are accurately represented and as much data is collected as possible. The deeper offshore areas can be surveyed with single beam or Multibeam surveys as well. Ideally the survey extends out into the channel as far as the bar deposit does. However, as a minimum rule of thumb the survey should extend at least out to previous survey extents. DoDs can only be calculated where the input extents overlap; therefore, collecting offshore data one year and skipping others provides no benefit to that DoD.

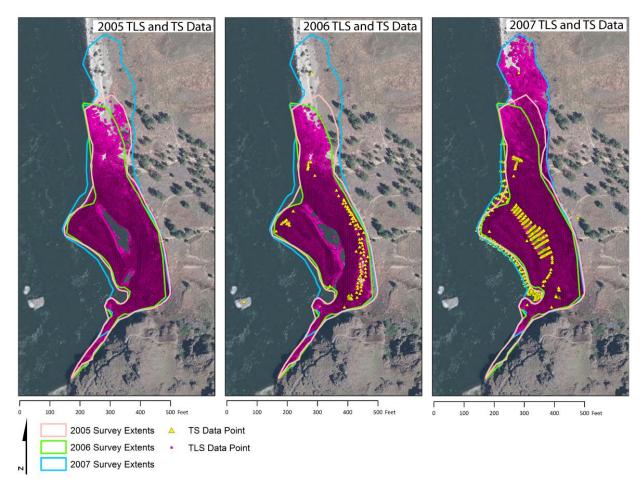


Figure 4 - Pine Bar TLS and TS data for 2005, 2006, and 2007. Notice gaps in TLS data where TS data could have been collected to fill in gaps.

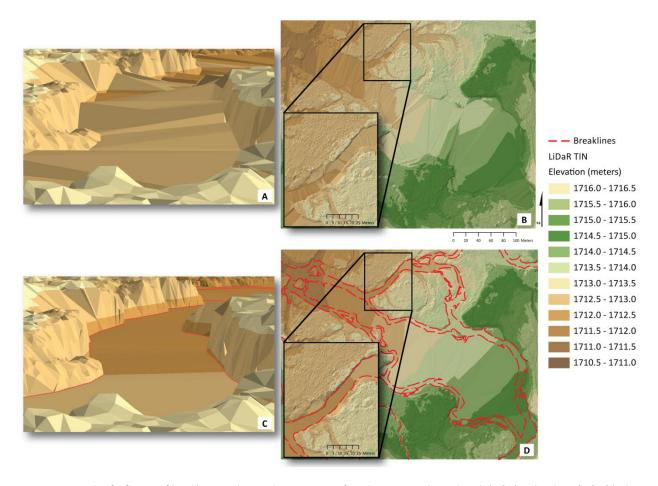


Figure 5 – Example of influence of breaklines on data quality, LiDaR TIN of Lemhi River sample reach with (C &D) and without (A & B) hydroreinforced breaklines. Figure from Portugal et al. (In revision).

TLS DATA POST PROCESSING & PREPARATION

TLS data post processing and preparation can be done in a variety of point-cloud software packages, but it is often simplest and most productive to use the software of the manufacturer of the scanner used to acquire the data. As IPC data was collected with a Leica ScanStation, we used Leica's Cyclone software. To our knowledge, Cyclone software is something IPC staff does not currently have a license for. This processing has largely been done by a contractor, which will need to continue unless IPC purchases the Cyclone software. The post processing of IPC TLS data has been up to industry standards, based on the data we have reviewed (Table 1). However, clearer instructions should be provided to vendors responsible for post processing IPC data. Unfortunately, for the 2005, 2006 and 2007 datasets we were provided at China Bar and Pine Bar, the data was appropriately post-processed but since that data was not projected into the Idaho Power Coordinate System (IDPCS), we were forced to redo virtually all of this manual post-processing. Therefore, the money, time, and effort spent to have the contractor do this was duplicative. We highly recommend that data is registered in Idaho Power Coordinate System (or whatever coordinate system IPC prefers to work in) before data is cleaned in Cyclone.

¹ This is a functional limitation of the Cyclone software and the particulars of which common control points were and were not available in both the IDPCS and native coordinate system of the scanner.

ENSURING TLS SCANS ARE IN COMMON IPCS

Before undertaking any change detection analyses, it is essential to ensure that all the raw topographic data are transformed into a common coordinate system and/or projection. Change detection can be performed in assumed local Cartesian coordinate systems, but having the context of other GIS layers is a compelling reason to work in a real world coordinate system (either projected or geographic). Geographic coordinate systems have small differences in the grid cell area for raster data, whereas projected coordinate systems have a constant cell area. As volumetric change detection analyses rely on the multiplication of vertical change values by a cell area, it is desirable and simpler to stick with projected coordinates.

As the Idaho Power service area spans multiple states and UTM projection zones, they have developed their own projection centered on their service area. The IPC projection is a transverse cylindrical conformal projection. This projection is similar to the Mercator except that the cylinder is longitudinal along the central meridian instead of the Equator, and is tangent to the ellipsoid at the secants created by the scale factor and not the central meridian. Therefore, scale is true and equal to "one" at the secants, and small amounts of position error will increase/decrease away from the secants toward the exterior of the service territory (this is analogous to having two central meridians). The result is a conformal projection that does not exactly maintain true direction, but maintains true shape. The central meridian is placed at the center of the service territory. This centering minimizes distortion of all properties in that region.

Parameters:

Transverse (cylindrical conformal) Projection

Units: Feet (US Survey Feet), Horizontal Datum: NAD83,

Vertical Datum: NAVD88, (NAD83 NSRS2007) ellipsoid heights in Hells Canyon

Scale Factor at Central Meridian: .99960, Longitude of Central Meridian: -115 30 00,

Latitude of Origin: 42 00 00,

False Easting: (Meters) 500000 or (US Survey Feet) 1640416.666667, or False Northing: (Meters) 100000 or (US Survey Feet) 328083.333333.

CO-REGISTRATION

In Cyclone, co-registration is the process of georeferencing all of the individual scanworlds (i.e. scans from specific scanner setups) into a common coordinate system. In this case, the scans were already co-registered, but we transformed them into the Idaho Power Coordinate System (IDPCS). This co-registration is derived by using a system of constraints, which are pairs of common points that exist in the scanworlds being co-registered. The objects involved in these constraints are maintained in a control space, where they can be reviewed, organized, and removed. They cannot be moved or resized in the control space. The registration process computes the optimal overall alignment transformations for each component scanworld in the Registration, such that the constraints are matched as closely as possible.

Registration of scanworlds is a necessary step because TLS and TS data are not collected in the IDPCS; therefore, steps must be taken to get data into the IDPCS.

- 1. In Cyclone, select database to be registered by clicking on icon (Figure 6)
- 2. Click 'Create' → 'Registration' to create a registration file

- 3. Double click on the registration icon to open the file. In the Registration window click 'ScanWorld', then click 'Add ScanWorld' to open dialog box
- 4. Highlight the control scanworld and click to add the scanworld to the registration



Figure 6 - File structure in Cyclone showing files associated with the 2005 China Bar survey. Registration file is highlighted.

UNIFICATION OF SCANS

Unification of scans is the process of compiling all of the separate point clouds from individual scanworlds into one large point could. Individual scanworlds must be unified into one large point cloud before the cleaning of TLS scans. It is recommended that a duplicate modelspace is created before unification so that an original exists. To create a duplicate modelspace right click on original modelspace, click on 'Create', click on 'ModelSpace'.

Prepare the new modelspace to be unified by selecting the individual scan data. To do this open the new modelspace, click 'Tools', click 'Scanner', click 'ScanWorld Explorer'. A dialog box similar to the one in Figure 7 will appear. This particular dialog box shows three scanworlds with fourteen scans, ScanWorld 18 and Scan 2 are selected/highlighted in Figure 7. For each scanworld, go through the individual scans and determine which scans are of use and which are not. Fine scans are of no use and can be deselected by turning off the check mark in the 'Show Cloud' check box; Figure 7 has no fine scans. Scans of targets are only useful for co-registration and can also be deselected in the 'Show Cloud' check box. To assist in determining which scans are useful, the 'Field of View' (FOV) of each scan can be toggled on and off using the FOV check box (Figure 7). In Figure 7 there are four scans selected in the 'Field of View' column, all of which can be seen from the green lines in the model space. It is also helpful to zoom in on these scan locations and confirm they are scans of targets.

Again, go through each scanworld and only select the scans needed for the final, unified point cloud. When satisfied that the appropriate scans are selected proceed with unification. To unify the point clouds, click 'Tools', click 'Unify Clouds', and click 'Unify' in the dialog box (left side Figure 8), click 'Unify' in the dialog box (right side Figure 8). With the dialog box on the right side of Figure 8, it is possible to eliminate some points using a three dimensional spacing. It is not recommended to reduce point cloud spacing in Cyclone, this process is done at a later step with PC-Tools. Depending on the quantity of points, the unification process can take a couple of minutes to an hour to complete.

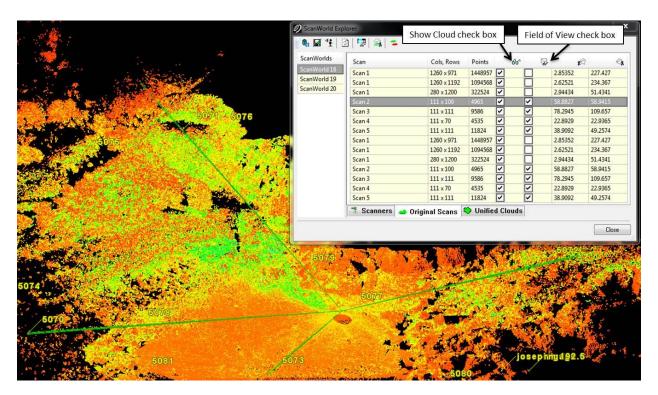


Figure 7 – Dialog box for ScanWorld Explorer where individual scans are selected for unification and associated scans from modelspace.



Figure 8 – Dialog boxes for which scanworlds are unified into one point cloud.

MANUAL CLEANING OF TLS SCANS

Using a unified point cloud, the next step is to clean the point cloud. The cleaning process is the removal of points representing foreign objects such as: boats, people, pelican cases, generator, targets, tripods etc. (Figure 9 and Figure 10). To create the resultant ground surface foreign objects must be removed from the TLS data. Use the 'View Mode' tool and the 'Seek(S)' tool to move through the point cloud and search for foreign objects to delete them. Objects may be easier to see using the 'Cloud Density Reduction' tools 'Use Hue Intensity Map' tool , and the 'Point Width' tools . There is no best way to view a point cloud; trial and error will be part of determining which view is most helpful. When maneuvering through a point cloud and foreign objects are detected for deletion, use the 'Polygon Fence Tool' to frame the foreign objects (white box in Figure 10), right click, click 'Fence', and click 'Delete Inside' (or click 'Edit', click 'Fence', and click 'Delete Inside'). All points within the fence are deleted, from the computer screen back to infinity in three dimensions. After points are deleted Figure 10 now looks like Figure 11. Make sure there are no points hidden behind the points planned for deletion. This will delete the points from the ModelSpace View and the corresponding ModelSpace. One way to subset out a section of the ModelSpace View to help prevent deleting unnecessary points is to click 'View', click 'Set Limit Box by Fencing', and left click and scroll to draw box (yellow box in Figure 10 and Figure 11). This limits the points viewed to those that were selected within the defined box. Now it is possible to move within this box and delete the appropriate points (Figure 10 and Figure 11).

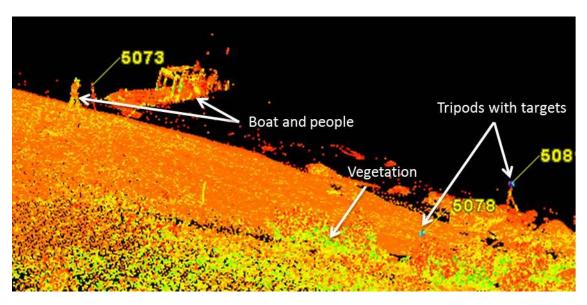
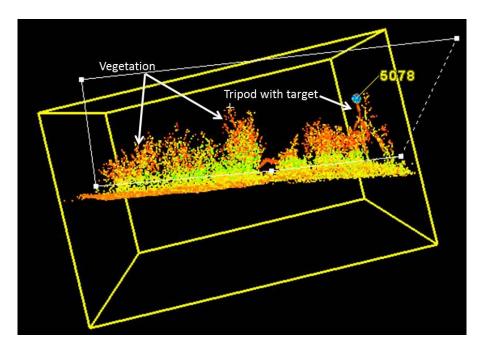


Figure 9 – Unified point cloud that needs cleaning of points not representing the ground surface: boat, people, tripods, targets and vegetation.



 $\label{eq:Figure 10-Point cloud with foreign objects fenced, white box, for deletion. \\$

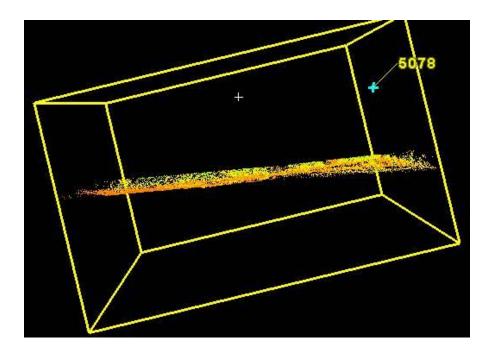


Figure 11 – Point cloud after deletion of vegetation, tripod and target.

EXPORT OF SCANS TO PTS FILE

After all foreign and undesirable objects are removed from a ModelSpace the points are exported to a point file (.pts), providing an XYZ coordinate for each point, in order to further analyze the data.

- 1. Export '.pts' file from Cyclone
 - a. Open Cyclone–Navigator → Servers → database → Scan World Registration → ModelSpaces → Cleaned and Unified Model Space (Figure 12)
 - b. In ModelSpace window:
 - i. File → Export... → navigate to where file will be stored → name file → click 'Save' → check 'Object Type' box and 'Point Cloud' box in 'Export Options' dialog box → click 'Export' (Figure 12)

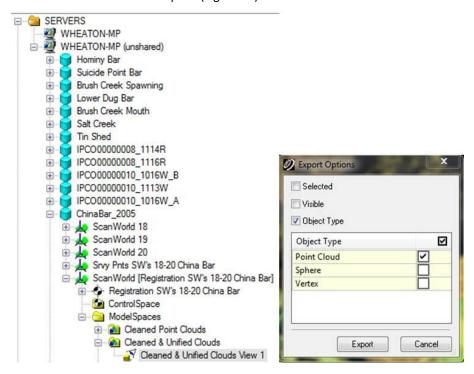


Figure 12 - Figure shows data structure in Cyclone-Navigator and 'Export Options' dialog box when exporting a point file (.pts)

DECIMATION OF SCAN DATA IN PC-TOOLS

After foreign objects have been removed from the point cloud, a decimation process is run on the data to make the dataset more manageable to deal with, derive statistical models of error, derive bare earth and roughness approximations. The decimation process can be run on the data with or without vegetation having been manually 'mowed'. Manual mowing, will skew the roughness results toward lower values, but can also produce more reliable estimates of bare earth in some situations.

In PC-Tools:

- 1. Place exported '.pts' file from Cyclone into the same folder that contains PC-Tools (Figure 13)
- 2. In the PCTools folder, Right click on 'run.bat', and click 'Edit'
 - a. Edit the name of the '.pts' file to reflect correct name (Figure 14)

- i. Multiple '.pts' files can be included in the 'run.bat' and they will be processed sequentially as they are listed.
- b. For 1 foot decimation use a xres of 1, yres of 1, nmin of 4, zmin of 0, zmean of 1, and stdev of 0
 - The xres and yres will need to be changed for each decimation/grid resolution desired.
 Since the scale is in feet, decimating at .25 is actually a decimation of 3 inches (a quarter of 12 is 3).
- 3. In Start Menu search window type 'cmd' and click on 'cmd.exe' program
 - a. At end of first prompt line type 'cd\' and hit return (Figure 15)
 - b. At end of second prompt line type 'cd pctools' and hit return (Figure 15)
 - c. At end of third prompt line type 'run.bat' and hit return (Figure 15)
- 4. Step 3 can be accomplished by double clicking on 'run.bat' Windows Batch File
- 5. Move the four created .txt documents from PcTools folder (highlighted below in Figure 13) to relevant folder and delete the three other created files

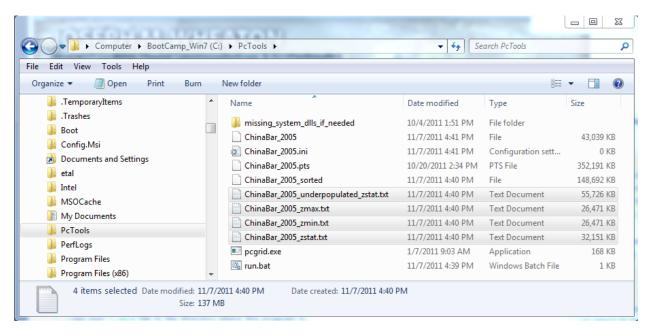


Figure 13- PC-Tools folder with output from decimation process.

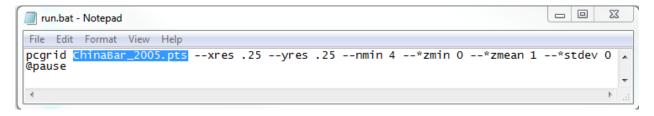


Figure 14 – Display of run.bat file from PC-Tools showing inputs for decimation process.

```
C:\Windows\system32\cmd.exe - run.bat
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation. All rights reserved.
C:\Users\Ryan Leary>cd\
C:\>cd pctools
C:\PcTools>run.bat
C:\PcTools>pcgrid ChinaBar_2007.pts --xres 1 --yres 1 --nmin 4 --*zmin 0 --*zmea
         ∗stdev Ø
n 1 --*stdev 0
Please wait...
$kippping line #1: 9432142
9432144 lines and 9432142 points
is 32-bit build enough? ...yes
number of cells at this resolution: 148617
indexing points into grid...
9432142 points
85672 empty cells
85672 empty cells
15536 maximum number of points per cell
riting the sorted point cloud...
148617 cells
(working with sorted point cloud file)...
writing the grid statistics...
8708 underpopulated cells
Press any key to continue
```

Figure 15 - cmd.exe window for entering commands to run decimation process.

WHAT RESOLUTION(S) TO DECIMATE TO?

Point-cloud-tools software allows TLS data to be decimated to a grid at a defined grid resolution, providing the possibility of analyzing TLS data in ArcGIS. Without decimation, TLS datasets are generally too large for ArcGIS to handle (Rychkov et al., 2010). A byproduct of decimation are minimum and maximum elevation coordinates from each cell, as well as grid centered statistics. The minimum coordinates are a reasonable approximation of bare-earth and commonly used to build bare earth topographic surfaces. The size of the cell at which decimation occurs dictates the resolution of the data from which TINs or Terrains may be created in, for example, ArcGIS. The size also controls their subsequent accuracy and processing time. The main question here is what decimation/cell size is appropriate for capturing high resolution data without losing important information or keeping excess information which can make analysis cumbersome. An appropriate decimation resolution can be determined on the basis of an information loss sensitivity analysis and visual inspection of what features are still resolved in the modeled surfaces.

Using point-cloud-tools software, a range of cell sizes was selected in which to decimate the exact same TLS data. TLS data collected in 2005 at China Bar was decimated at the following cell sizes: 0.25 ft, 0.5 ft, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 7 ft, and 10 ft. Digital elevation models (DEMs) were then built in ArcGIS 10 using the minimum value from each cell for each level of decimation and visually compared. The results from the created DEMs at each of the decimated grid resolutions are shown in Figures 16 and 17.

Using each DEM, slope and curvature raster's were created in ArcGIS 10. Profile and plan curvature raster's were also created from each DEM. Profile curvature is the curvature of the surface in the direction of slope and plan curvature is the curvature of the surface perpendicular to the slope direction. The summary statistics (minimum, maximum, mean, and standard deviation) for these 36 raster surfaces were input into Microsoft Excel to compare each grid resolution graphically. Figures 18 and 19 show the results for the curvature raster's, Figure 20 shows the

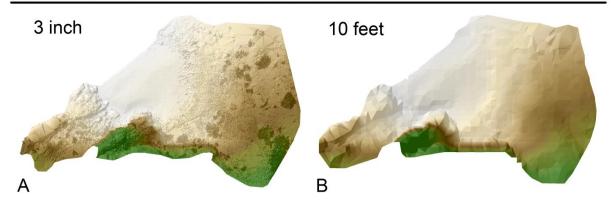
results for the plan curvature raster's, Figures 21 show the results for the profile curvature raster's, and Figure 21 shows the results for the slope raster. There are two figures for each pair of curvature raster's since the scale in Figures 18 and 20 are large enough to not show the change in slope for standard deviation in Figures 19 and 21.

Click here for PC-Tools. Or go to http://www.joewheaton.org/Home/research/unlisted-software/point-cloud-tools

Figures 16 and 17 show the results of the visual analysis created DEMs for each level of decimation. As the cell size for decimation increases, the amount of topographic detail resolved decreases. Many of the micro topography features on the sand bar are captured up to a grid resolution of about 1 foot (e.g. footprints, ripples, etc.). Outside the sandbar in the boulders and vegetated areas, the coarser resolution data smooth's and generalizes the topography.

Figures 18 through 22 show information loss graphs comparing the summary statistics of various morphometric analyses derived from each DEM for the whole range of decimation resolutions process. In all of the curvature graphs, the minimum, maximum, and standard deviation values show a change in slope with the inflection starting around 1 foot and extending up to a decimation of 3 feet. Flat graphs indicate that a derived value is not changing (i.e. not sensitive to a particular range of grid resolution values). There are two ways to typically interpret breaks in slope leading to a flat portion in information loss graphs: When a flat portion in the graph is reached, it can be interpreted either as 1) a scale-threshold has been crossed and topographic features of a different scale are being captured (e.g. difference between characterizing form roughness and grain size roughness topographically); or 2) an accuracy threshold has been crossed (above which) further increases in resolution do not distinguish features any further. As the lower limit for this analysis was 3 inches (due to practical computational limitations and the 0.03 inch maximum attainable resolution of actual scan points), a type 2 break in slope is never reached in these graphs. In contrast a type 1 flat spot moving up in resolution is reached. However, a second grade break with an upper limit of 10 feet is never fully reached.

Reference - Finest and Coarsest Resolutions



Intermediate Resolutions

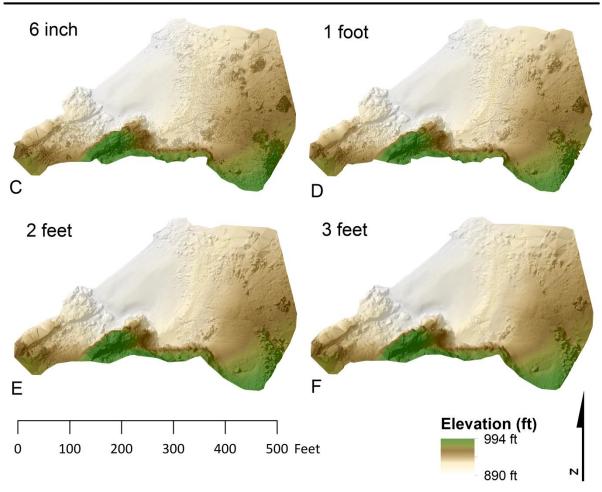


Figure 16 - DEM comparison of different decimated grid resolutions.

Reference - Finest and Coarsest Resolutions

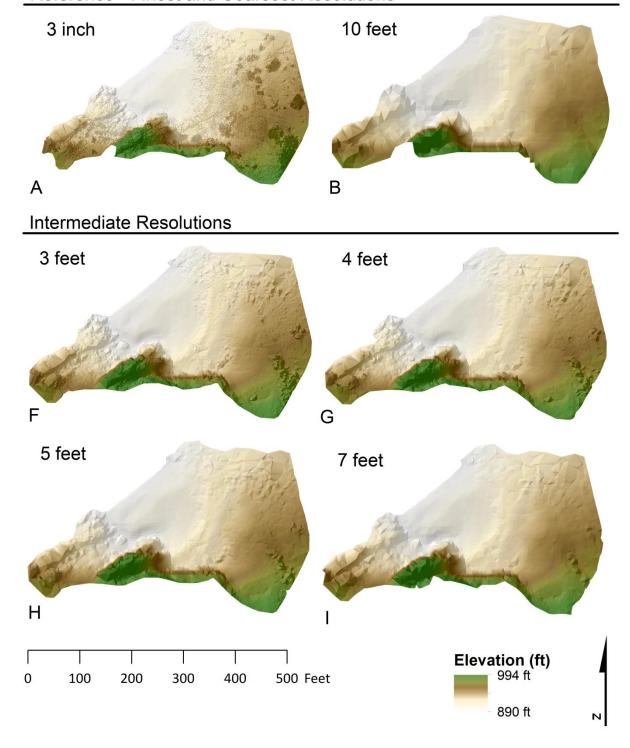


Figure 17 – DEM comparison of different decimated grid resolutions.

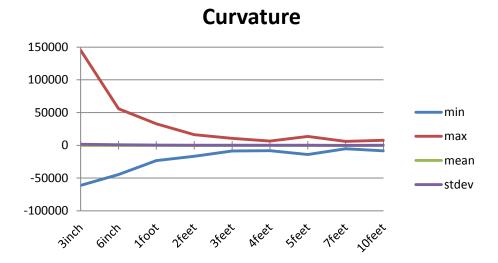


Figure 18 – Summary statistics for curvature raster's over a range of grid resolutions from PC-Tools.

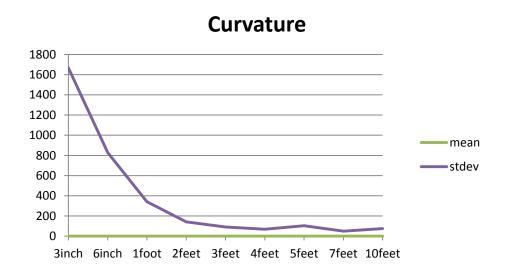


Figure 19 - Summary statistics for curvature raster's over a range of grid resolutions from PC-Tools.

Profile & Planform Curvature

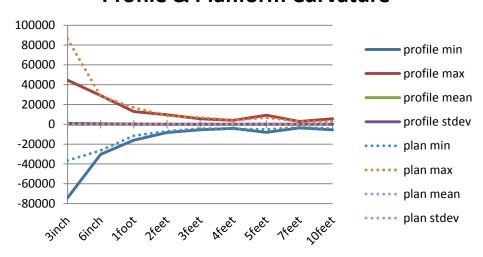


Figure 20 - Summary statistics for profile and planform curvature raster's over a range of grid resolutions from PC-Tools.

Profile & Planform Curvature

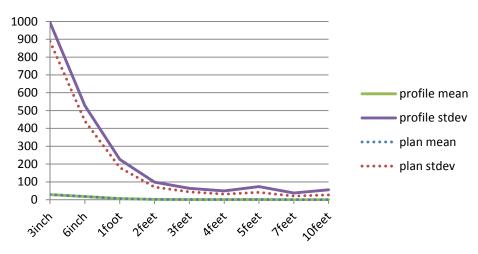


Figure 21 – Zoomed in of Figure 19, mean and standard deviation for profile and planform curvature raster's over a range of grid resolutions from PC-Tools.

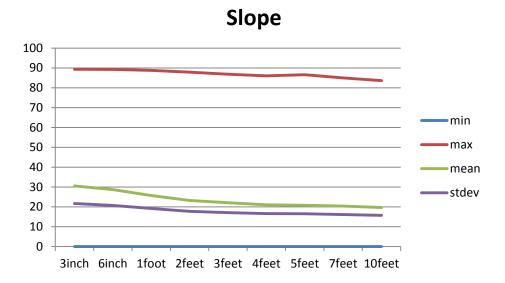


Figure 22 – Summary statistics for slope raster over a range of grid resolutions from PC-Tools.

Figures 16 and 17 illustrate how decimating at a smaller grid resolution results in a higher resolution DEM image. However, defaulting to the smallest cell size that the software will process is not desirable (here it was 3 inches) because if the cell size is too small the lowest elevation point may not actually be the ground surface and could be some level above the ground (e.g. vegetation extending above the ground). Based solely on visual inspection of features maintained in the DEM, it appeared that at the 1 foot level enough data was maintained for a high resolution DEM. Also, given the extremely high resolution of the TLS data (e.g. point spacing of 1-10 mm) we can be confident that decimation at 1 foot will provide accurate data since we know our point cloud is hitting all bare earth in the areas covered by the smooth surface of the sand bar.

In areas that are covered by uneven, rough, and possibly vegetation we will want to consider a different level of decimation. To insure that we are getting data from the ground surface, especially for minimum values, we will want to choose a grid resolution larger than 1 foot. A Visual inspection of the lines representing mean and standard deviation of slope in Figure 22 reveals a leveling off at the 5 feet cell resolution and above. This suggests that a scale-threshold has been crossed at finer resolutions than 5 feet and topographic features of a different scale are being captured with 5 foot and above resolution.

Figures 18 through 22 show information loss graphs comparing the summary statistics of various morphometric analyses derived from each DEM for the whole range of decimation resolutions process. In all of the curvature graphs, the minimum, maximum, and standard deviation values show a change in slope with the inflection starting around 1 foot and extending up to a decimation of 3 feet. Since standard deviation is a measure of variability, or how much variation there is from the mean, we can use this as a way to show when variability decreases and becomes consistent regardless of grid resolution used for decimation. The largest change in slope for standard deviation occurs at approximately 1 foot in each of the curvature figures (Figures 18, 19, 20, and 21). This inflection point suggests that a scale-threshold has been crossed at 1 foot cell resolution and below, meaning these resolutions are characterizing topographic features of a finer scale.

Based on this analysis, we would recommend a decimation of 1 foot for areas covered by the sand bar and a decimation of 5 feet where there are uneven surfaces due to boulders and vegetation.

TLS BARE EARTH SURFACE MODELING

Bare earth surface models represent the earth's surface without any objects such as plants, boats, scan equipment, or buildings. Bare earth surface models can be constructed in many ways and are important for monitoring geomorphic changes. Here we use TLS data from IPC to build bare earth surface models by constructing TINs and DEMs from topographic survey data.

A Triangulated Irregular Network (TIN) interpolates between raw topographic survey data to produce a continuous surface that is later converted to a raster DEM. The density of point data influences the quality and appearance of a TIN. Without high density data, like TLS data, it would be very important to collect meaningful information such as point type (e.g. offshore, topo, edge of water) to go along with the x, y, z information already being collected. When collecting data with only a Total Station, labeling points becomes important so that breaklines can be used when building a TIN. When building a TIN use hard breaklines for sharp breaks in slope, such as the top of a bank, and soft breaklines for more gradual slopes. Breaklines can be created in Cyclone but for higher quality data it is recommended that breaklines be collected in the field with a Total Station. Here, we did not need breaklines since the majority of data was collected using TLS.

A TIN is one way to digitally represent 2.5D surfaces. Many programs require terrain to be represented in a raster format, which is a uniformly gridded representation of the data at some particular resolution. Since it is easier to write algorithms and codes for analyses of raster data, there are many more tools available for analyzing DEMs than TINs. Two of the biggest challenges when working with DEMs are: a) getting data from whatever format it is provided in and translating it into a format you can work with; and b) getting it to work and look how you want.

BUILDING A SURFACE FROM DECIMATED TLS DATA / TIN CONSTRUCTION

The first step in building a surface from decimated TLS data is to bring the exported '..._zmin.txt' file from PC-Tools and any Total Station (TS) data available for a particular site in a specific year into ArcGIS. Be sure that .txt files have a header row before being added to ArcGIS. Steps 2 and 3 involve creating shapefiles and merging them if necessary. Step 4 outlines the process for creating TIN surfaces.

- 1. In ArcGIS: File → Add Data → Add XY Data... (Figure 23)
 - a. Click folder icon and navigate to text (.txt) file to be imported
 - b. Populate the fields for the X, Y and Z coordinates
 - c. Select the coordinate system of the input data by clicking 'Edit..', 'Select...', and navigating to appropriate coordinate system
 - d. Click 'OK' and point data is automatically added to ArcGIS Table of Contents (TOC) (Figure 24)

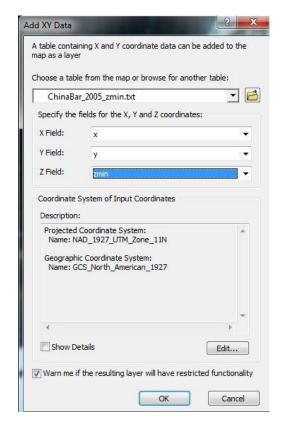


Figure 23 – Dialog box for importing data into ArcGIS. TLS data collected in 2005 from China Bar is being imported here.

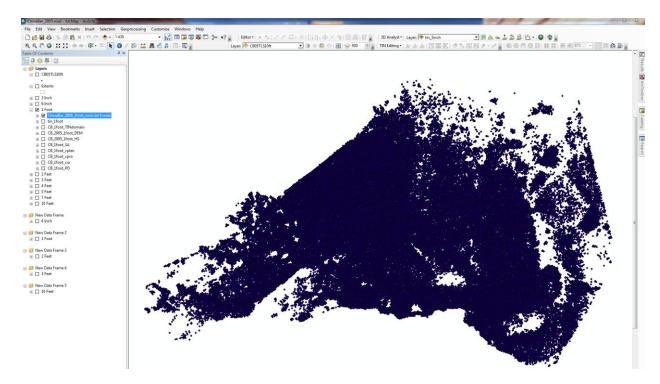


Figure 24– Raw XY point data added into ArcGIS from China Bar 2005 TLS data decimated at 1 foot.

- 2. Export 'Events' data file and create shapefile
 - a. In ArcGIS right click on layer to be exported → Data → Export Data...
 - i. In Export Data dialogue box:
 - 1. Export All Features
 - 2. Select 'this layer's source data' radial button
 - 3. Select location where to Output feature class by clicking on folder icon name shapefile, click 'Save'
 - 4. Click 'OK' and add exported data to the map as a layer
 - 5. 'Events' file can be removed by right clicking on it and selecting 'Remove'
- 3. If more than one shapefile is created for a specific site in a given year then merge into one shapefile (this will be appropriate when both TLS and TS data are collected)
 - In ArcToolbox: Data Management Tools → General → Merge; OR, in Search window type 'merge', then click on 'Merge (Data Management)' (see Figure 25)
 - c. In Merge dialogue box (Figure 26):
 - i. Select files to merge using dropdown list, clicking on folder icon and navigating to files, or dragging files into 'Input Datasets' field
 - ii. Select location where to Output Dataset by clicking on folder icon iii, name the feature classes, click 'Save'
 - iii. Click 'OK' (Layer is automatically added to TOC)
 - d. When merging shapefiles make sure that the column headings are the same (i.e. z vs. zmin)

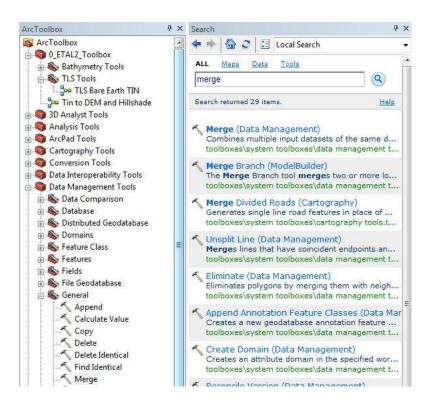


Figure 25 - Both the structure and navigation in ArcToolbox window and the Search window are shown for how to retrieve the 'Merge' tool.

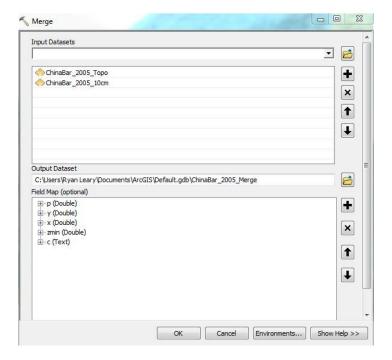


Figure 26 – Merge dialog box used for merging multiple shapefile into one (e.g TLS and TS data)

- 4. Create TIN from point shapefile(s)
 - a. In ArcToolbox: 3D Analyst Tools → TIN Management → Create TIN; OR, in Search window type 'create tin', then click 'Create TIN (3D Analyst)' (see Figure 27)
 - b. In Create TIN dialogue box (Figure 28):
 - i. Select location to save TIN by clicking folder icon in Output TIN window
 - ii. Select the same Spatial Reference as you are currently working in
 - Click Spatial Reference icon , click 'Import' button, and select a file that is currently in TOC and has defined spatial properties or click and navigate to spatial reference
 - iii. Select shapefile, from which TIN is made from, using dropdown list, clicking on folder icon and navigating to file, or dragging file into 'Input Feature Class' field
 - iv. In 'height_field' make sure 'z' or 'zmin' is selected
 - v. Click 'OK' (TIN is automatically added to TOC)

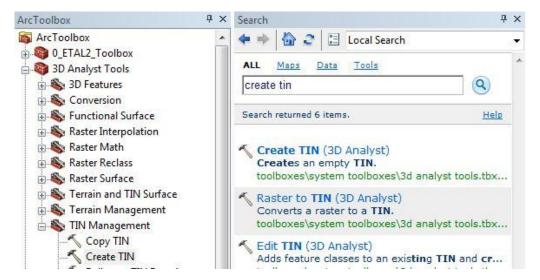


Figure 27 – Both the structure and navigation in ArcToolbox window and the Search window are shown for how to retrieve the 'Create TIN' tool.

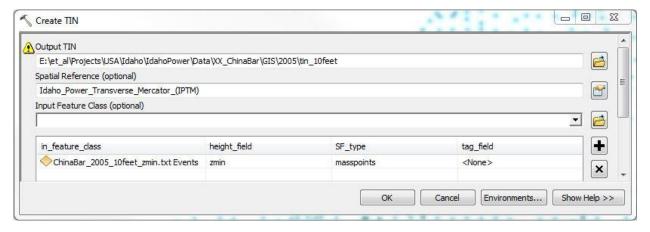


Figure 28 - Dialog box used for creating TINs

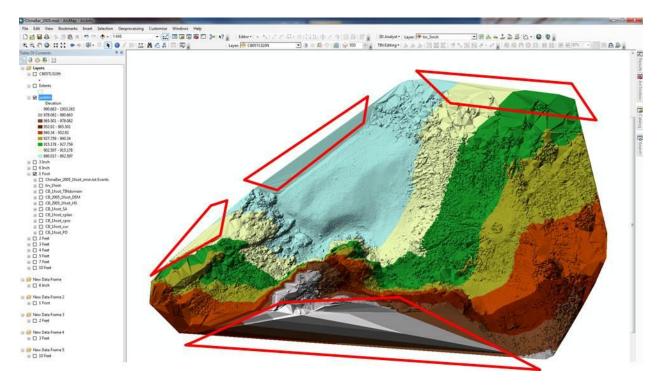


Figure 29 – Original, unedited TIN created using raw XY point data from China Bar 2005 TLS data decimated at 1 foot. Areas within red outline have been interpolated.

TIN EDITING

Although building a TIN is easy, it is also easy to build a TIN that misrepresents your data. It is important to build TINs that accurately represent the data and avoid over interpolation of areas. Notice the areas outlined in red in Figure 28. The TIN algorithm interpolates across these areas, even though no survey data was collected, by connecting the dots between the closest points. Although this may be a crude approximation of the surface, it is NOT an accurate or honest representation of the survey data. Interpolated areas should be removed from TINs so that they are not used when building DEMs.

- 1. TIN cleaning and editing
 - a. Add 3D Analyst and TIN Editing toolbars by right clicking in gray space near top of ArcMap and selecting '3D Analyst' and 'TIN Editing'
 - b. TIN layer must be selected in 3D Analyst Layer window (Figure 30)



Figure 30 – TIN Editing and 3D Analyst toolbars showing TIN being edited and tools available for editing.

- c. In TIN Editing toolbar (Figure 30):
 - i. Click 'Start Editing TIN' from TIN Editing dropdown list

- ii. Click on the Modify TIN Data Area icon and "clean" TIN by deleting interpolated areas (Figure 30)
 - 1. In the Modify TIN Data Area dialog box select 'within polygon' and 'set outside'
- iii. Save often, since edits can only be undone since last save!!

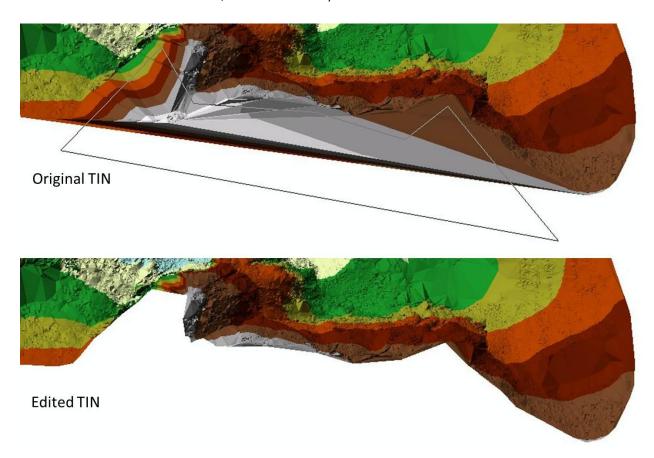


Figure 31 – Comparison of zoomed in portion of original and edited TIN.

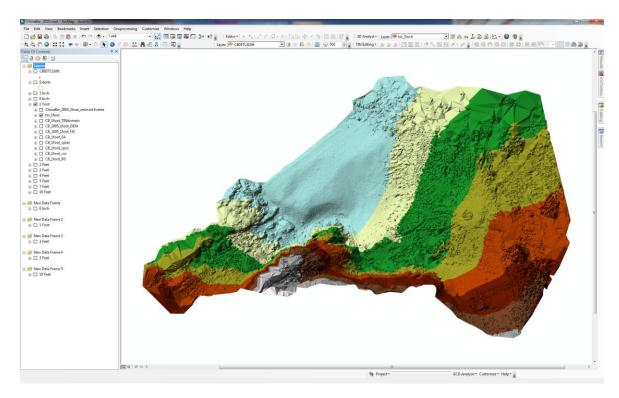


Figure 32 - Edited TIN of Figure 31 above.

MAKING CONCURRENT RASTERS WITH EXTENTS SHAPEFILE

Regardless of raster resolution, all raster files used in the Geomorphic Change Detection (GCD) software must have the same extents and be orthogonal, making them concurrent. Raster files must be concurrent in the GCD software in order to perform map algebra on a cell by cell basis, leading to the accurate production of DEMs of Difference (DoDs). Concurrent rasters share the exact same grid resolution and grid centers (i.e. aligned in both easting and northing) and also have the exact same spatial extent. When creating an extent shapefile use whole numbers so that it can be divided by the grid resolution. For more information on grid concurrency, a prerequisite for GCD, click here. The current version of GCD, GCD 5.X, has addressed this issue. If rasters being used in analysis are not concurrent the user is prompted if GCD should fix it automatically; although this corrects the problem it is best practice to deal with this manually ahead of time.

Steps required for creating an extents shapefile to be used in processing all raster files at a specific site for all years:

- 1. Create a new shapefile in ArcGIS
 - a. In Arc Catalog right click on folder where shapefile will be stored, click 'New', click 'Shapefile'
 - b. In 'Create New Shapefile' dialog box: name file, select 'Polygon' as the feature type, select spatial reference, and click 'OK' (Figure 33). Layer is automatically added to Table of Contents.
- 2. Edit shapefile to the proper extents
 - a. In Create Features box (Figure 34)
 - i. Click 'Organize Feature Templates' and create a New Template for new shapefile
 - ii. Click Polygon in Construction Tools box and draw a bigger than necessary, but not too big, rectangle around TIN and TLS/TOPO data (Figure 36)

b. Edit Vertices

i. Click on Extents box, click Edit Vertices icon from the Editor toolbar, and click

Sketch Properties icon from Edit Vertices toolbar

ii. Edit Vertices to whole numbers and desirable size (Figure 33)

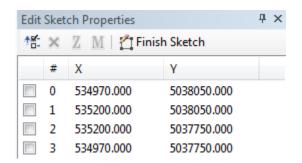


Figure 33 – Edit sketch properties dialog box showing vertices edited to whole numbers

c. Save Edits

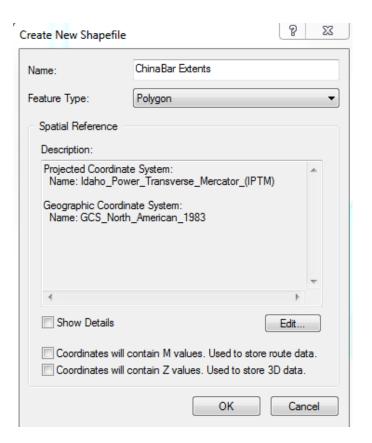


Figure 34 – Dialog box for creating new shapefiles

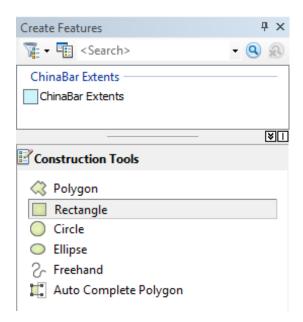


Figure 35 - Create Features box for creating extents rectangle

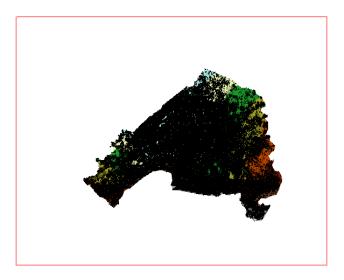


Figure 36 – Extents box (red box) drawn around study site. Extents box needs to be large enough to include each year's extent of data.

TIN TO RASTER DEM CONVERSION

A Digital Elevation Model (DEM) is a representation of the earth's surface for a geographic area stored in a digital file containing regularly spaced point locations with an elevation attribute. TINs must be converted to raster DEM data in order to calculate and detect changes in elevation for a given area. Once a TIN is converted to a DEM, a Hillshade can be created from the DEM. Hillshades are the illumination of a surface based on the topography and a hypothetical light source. Hillshades are commonly used to visualize topography and terrain and are often used as a contextual backdrop to DEMs.

1. Create raster DEM from TIN

- a. In ArcToolbox: 3D Analyst Tools → Conversion → From TIN → TIN to Raster; OR, in Search window type 'tin to raster', then click 'TIN To Raster (3D Analyst)'
- b. In TIN to Raster dialogue box (Figure 37):
 - i. In 'Input TIN' field select TIN by clicking folder icon and navigating to file, OR dragging file into 'Input Tin' field
 - ii. In 'Output Raster' field navigate to folder where DEM will be saved by clicking on folder icon
 - 1. '.img' must be added to the end of the file name for the file to work in GCD software
 - iii. Select 'FLOAT' in the 'Output Data Type' field
 - iv. Select 'Natural Neighbors' in the 'Method' field
 - v. In the 'Sampling Distance' field select a CELLSIZE of 0.25
 - vi. Use the default Z factor
 - vii. Click on 'Environments...', -> 'Processing Extent', and navigate to Extents shapefile
 - viii. Click 'OK' (DEM automatically added to TOC)

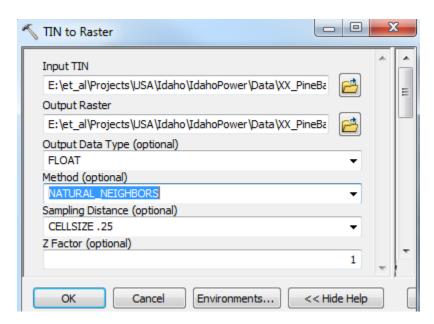


Figure 37 - Dialog box for converting a TIN into a raster DEM.

Choice of raster resolution (Sampling Distance field) is very important for two reasons 1) what topographic features can be resolved; and 2) computation time. In cases where raster extents are quite large (i.e. 10's to 100's of km²) 2 is critical. However, in cases of discrete sites (e.g. small sandbars generally < 1 km²) like Pine Bar or China Bar grid resolution doesn't limit computation time so we choose 0.25 ft (3 inches) as the cell size. A lower limit on grid resolution is defined by what is computationally possible as well as maximum resolution of the technique used to collect data. You want to be sure to select a cellsize for a DEM that is not smaller than the capabilities of the equipment used to collect the data in the field. Although we choose 0.25 ft as the cellsize for DEMS, an information loss analysis could be done to find the cellsize that best suits the data. However, we feel 0.25 ft is

suitable given the size of the sand/gravel bars in the IPC data set, since 0.25 ft is of high resolution, and the fact that we are trying to detect large bar size changes and not trying to detect changes as small as individual ripples.

2. Create Hillshade from DEM

- a. In ArcToolbox: 3D Analyst Tools \rightarrow Raster Surface \rightarrow Hillshade; OR, in Search window type 'hillshade', then click 'Hillshade (3D Analyst)'
- b. In Hillshade dialogue box (Figure 38):
 - i. In 'Input Raster' field select raster by clicking folder icon and navigating to file, OR dragging file into 'Input Raster' field
 - ii. In 'Output Raster' field navigate to folder where Hillshade will be saved by clicking on folder icon
 - iii. Use the default Azimuth, Altitude, and Z factor
 - iv. Click 'OK' (Hillshade automatically added to TOC)

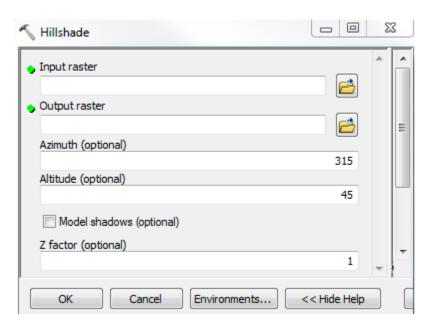


Figure 38 - Dialog box for creating a Hillshade from a DEM.

OPTIONAL - DIFFERENT DECIMATION LEVELS FOR VEGETATED AND UN-VEGETATED AREAS

Although it is recommended to decimate TLS data to 1 foot in PC-Tools, there may be situations where 1 foot decimation is not suitable across the entire study area. In areas with dense herbaceous ground cover or very uneven, course ground surfaces a lower resolution decimation may be more appropriate. Therefore, a combination of two decimations can be used to create DEMs which are used to produce DoDs: 1 foot for areas covered by the sand/gravel bar and a lower resolution decimation for areas outside the sand/gravel bar (Figures 38 to 40). We recommend a decimation resolution of 5 feet for areas outside the sand/gravel bar; however, this is flexible depending on the characteristics of a particular site. The selection of 5 foot resolution was made based on the shift in topographic features being captured at scales finer than 5 feet as revealed in the information sensitivity analysis on Pages 20 – 27.

Steps to create DEM using two levels of decimation:

- 1. Create polygon shapefile outlining sand/gravel bar
 - a. Use a basemap for context of sand/gravel bar extents (Figure 39). Keep in mind that the extent of a particular sand/gravel bar may change through time.
 - i. Click add data icon , click 'Add Basemap...', and double click on a basemap
- 2. Add both the 1ft and 5ft '_zstat.txt' files from PC-Tools into ArcGIS and create point shapefiles (see Pages 18 to 20)
- 3. Clip 1ft and 5ft point shapefiles using the polygon created in Step 1
 - a. 1ft point shapefile
 - i. In ArcToolbox: Analysis Tools → Extract → Clip; OR, in Search window type 'clip', then click 'Clip (Analysis)'
 - ii. In 'Clip' dialog box input 1ft point shapefile and sandbar polygon shapefile
 - b. 5ft point shapefile
 - i. In ArcToolbox: Analysis Tools → Overlay → Erase; OR, in Search window type 'erase', then click 'Erase (Analysis)'
 - ii. In 'Erase' dialog box input 5ft point shapefile and sandbar polygon shapefile
- 4. Merge clipped 1ft and 5ft point shapefiles (see Page 32)
- 5. Create and edit TIN from point shapefile (see Page 33-36)
- 6. Create DEM with TIN made from 1ft and 5ft point shapefiles (see Page 39)



Figure 39 – Aerial basemap with red polygon created in ArcGIS showing extents of sand bar at China Bar study site.

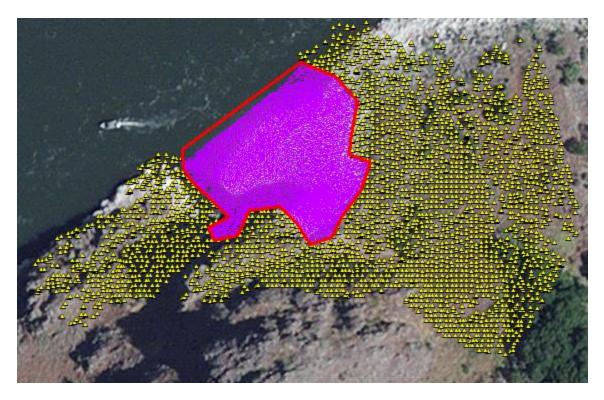


Figure 40 – 1ft decimation (19,533 purple dots in red polygon) used within the sandbar and 5ft decimation (3,264 yellow triangles) used for areas outside the sandbar at China Bar study site.

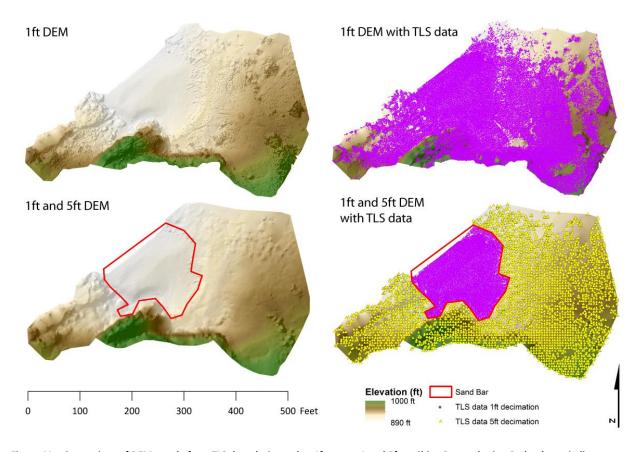


Figure 41 – Comparison of DEMs made from TLS data decimated at 1ft versus 1 and 5ft at China Bar study site. Red polygon indicates areas decimated at 1ft.

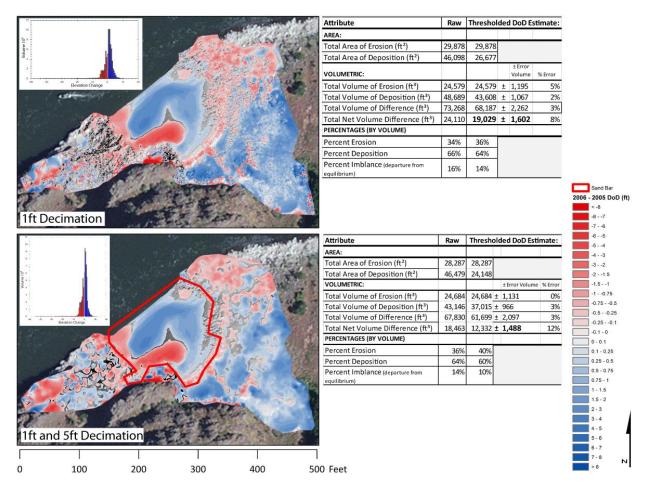


Figure 42 – Comparison of DEMs of Difference (DoDs) made from 1ft DEM versus 1 and 5ft DEM at China Bar study site. Red polygon indicates area decimated at 1ft. Simple minimum level of detection thresholded at 0.15ft used to produce DoDs.

VISUALIZATION

There are many ways a DEM can be displayed, but we find that a DEM is best displayed with a Hillshade below it. Hillshades are the illumination of a surface based on the topography and a hypothetical light source. Hillshades are commonly used to visualize topography and terrain and are often used as a contextual backdrop to DEMs. DEMs with Hillshades make changes in relief and surface roughness easier to visualize than DEMs without Hillshades (Figure 43).

DEMs can also be visualized with contour lines. Contour lines can be specified at any interval and allow the steepness of the ground surface to be easily visualized (Figure 43).

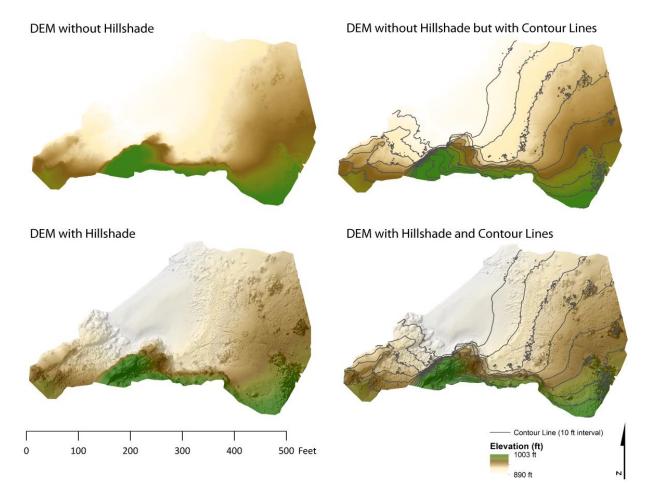


Figure 43 – 1ft DEMs from China Bar being shown with and without each of Hillshades and Contour Lines.

TLS SURFACE ERROR ESTIMATION

BACKGROUND

Given the uncertainty inherent in representing the earth's surface with a DEM, is it possible to distinguish real geomorphic changes from noise? Uncertainty is due to limited knowledge (e.g. inexactness, lack of observations or measurements, and/or practically immeasurable) that primarily arises out of unreliability from the surveying process and technology, and is exacerbated during the surface interpolation process. The reliability of morphologically inferred sediment budgets is controlled by: a) uncertainty in the flux boundary conditions; b) survey frequency; and c) DEM quality. It is important to recognize that the uncertainty of an output like an interpolated DEM surface is the result of propagated errors from the inputs (e.g. instrument precision, measurement errors in individual points), structural uncertainties in the sampling (e.g. point density, sampling pattern), surface composition and topographic complexity, and surface interpolation methods (e.g. TIN, inverse distance weighted, natural neighbors, spline, Kriging etc.).

There are a wide variety of ways to quantify uncertainties in the terrain surface representation of vector topographic survey data (i.e. x,y,z point clouds) as it is manifested in DEMs like those shown in Figures 16 and 17. A

commonly adopted procedure for managing DEM uncertainties involves specifying a minimum level of detection threshold (minLoD) to distinguish actual surface changes from the inherent noise. Determination of the minLoD requires both a theory of change detection and a metric of DEM quality (Brasington *et a.,.* 2000, Lane *et al.,* 2003). The approaches for approximating uncertainty range from as simple as assuming that the manufacturer reported instrument precision rating is a good indication of uncertainty, to attempts at complete error budgets (Lichti *et al.,* 2005).

Regardless of the approach used, the process of accounting for DEM of Difference (DoD) uncertainty follows a consistent progression through three steps:

- Quantifying the surface representation uncertainty in the individual DEM surfaces that are being compared;
- 2. Propagating the identified uncertainties into the DoD;
- 3. Assessing the significance of the propagated uncertainty.

The end goal is to propagate the estimated uncertainty in two DEMs into a DoD, to differentiate between those DoD calculated changes that are thought to be real versus those that cannot be distinguished from noise.

See Wheaton (2008) and Wheaton et al. (2010) for an in-depth look at uncertainty in morphological sediment budgeting in rivers.

SIMPLE MINIMUM LEVEL OF DETECTION

In ArcGIS, the raster calculator tool can be used to create a DoD raster surface by calculating the difference between each raster cell of two DEMs. This method uses no estimate of error and will provide the same output as a DoD created with the Geomorphic Change Detection software using a 'Simple minimum level of detection' with no threshold for uncertainty (i.e. no surface uncertainty at all). Although this is the same as using the raster calculator in ArcGIS, Geomorphic Change Detection software allows a threshold to be placed on the data (see Figure 44). This threshold is helpful because the most commonly adopted procedure for managing DEM uncertainties involves specifying a minimum level of detection threshold (minLoD) to distinguish actual surface changes from the inherent noise (Fuller et al., 2003). Predicted elevation changes that occur beneath this detection limit are typically discarded, or their probability of being real adjusted using a simple declining weighting function (Lane et al., 2003, p. 252). Typically, elevation changes above this minLoD are treated as real. There is, however, some inconsistency as to whether the propagated error used to estimate the minLoD should also be applied to changes over a threshold (e.g. if a minLoD of 10 cm was defined and the change was 15 cm, should it be 15 cm or 15 cm +/- 10 cm?). Determination of the _{min}LoD requires both a theory of change detection and a metric of DEM quality (Brasington et al., 2000; Lane et al., 2003). Typically, this is addressed applying the classical statistical theory of errors (Taylor, 1997) taking a measure of DEM precision derived from check data as a surrogate for DEM quality (Milan et al., 2007).

For Pine Bar and China Bar we used a minLoD of 0.15 ft (~1.8 inches or 4.6 cm) when calculating a simple minimum level of detection (Figure 44, 70, and 94). 0.15 ft was chosen as the minLoD since it closely approximates the error associated with TLS data from the scanner equipment (~1.2 inches or 3 cm) and TS data from total station equipment (~1.6 inches or 4 cm). DEMs of Difference (DoDs) should not be produced without at least accounting for the error associated with the equipment used for data collection. Given that 0.15 ft is slightly over the error associated with the equipment used for data collection, DoDs produced using a threshold of 0.15 ft will be slightly conservative. However, we purposely chose a slightly conservative value to use as a threshold since we decimated the TLS data, removing information and possibly adding uncertainty into the creation of bare earth surfaces for China Bar or Pine Bar.

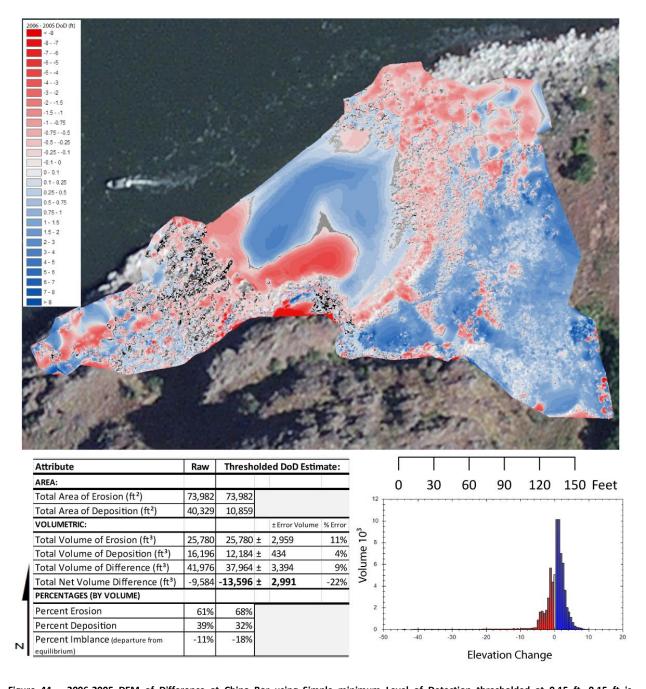


Figure 44 – 2006-2005 DEM of Difference at China Bar using Simple minimum Level of Detection thresholded at 0.15 ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

Figure 45 compares the influence of various $_{min}$ LoD thresholds (0.00m, 0.05m, 0.10m, 0.20m, and 0.50m) on DoDs and their elevation change distributions. All changes below the given threshold are assumed not to be real as they cannot be distinguished from noise. The more uncertain the DEMs (and hence the higher the $_{min}$ LoD threshold), the more information is lost from the budget. Clearly, we would expect elevation differences to occur across a continuum of values as suggested by the raw DoD. However, the significance of the uncertainty is the inability to reliably detect these lower magnitude elevation changes below the $_{min}$ LoD threshold.

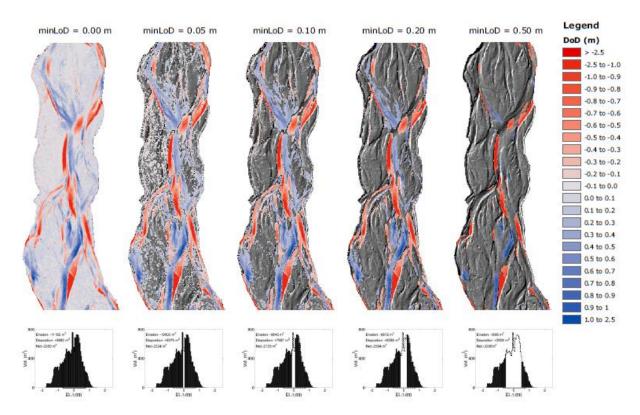


Figure 45 – Example of significance of elevation minLoD threshold on DoD budget for 2007-2006 DoD from the River Feshie, Scotland. The DoD maps are shown on top and the elevation change (El. Δ) distributions are shown below. The gross unthresholded DoD (simple LoD) is shown on the far left, and moving toward the right progressively more conservative (i.e. higher δ (DoD) and minLoD) are shown. From Wheaton et al. (2010).

UNIFORM ESTIMATE OF ERROR

Many techniques for estimating uncertainty in topographic survey data have the aim of collapsing the elevation (z coordinate) uncertainty down to a single global metric. Several techniques exist for measuring uncertainty using a uniform estimate of error but because they are spatially uniform, tend to be more conservative than necessary overall, but too liberal in certain areas. One of the simplest ways to treat uncertainty is to assume that it is spatially uniform and estimate its magnitude a) theoretically, b) from empirical experiments, or c) from numerical simulations. For example, with photogrammetric, total station, and GPS surveys one can make repeat observations of fixed control points over the course of a survey and look at the variance between the measurements (Brasington *et al.*, 2000, Lane *et al.*, 2003, Brasington and Smart, 2003). If one assumes that the variance or range in observations of a control point (that itself is assumed not to have moved) is indicative of the uncertainty in acquiring an individual topographic survey point, this may be reasonably used to approximate the uncertainty of all topographic survey points. Other techniques for estimating uncertainty in topographic survey data with a uniform estimate of error include complete error budgets (Lichti *et al.*, 2005), bootstrapping experiments (Wheaton, 2008), and repeat surveys of unchanging surfaces (Wheaton, 2008).

For Pine Bar and China Bar we used a propagated error of 0.15 ft (~1.8 inches or 4.6 cm) when calculating a uniform estimate of error (Figure 45, 70, and 94). 0.15 ft was chosen as the uniform estimate of error since it closely approximates the error associated with TLS data from the scanner equipment (~1.2 inches or 3 cm) and TS data from total station equipment (~1.6 inches or 4 cm). DEMs of Difference (DoDs) should not be produced without at least accounting for the error associated with the equipment used during data collection. Given that

0.15 ft is slightly over the error associated with the equipment used for data collection, DoDs produced using a uniform estimate of error of 0.15 ft will be slightly conservative. However, we purposely chose a slightly conservative value to impose on the error surface since we decimated the TLS data, removing information and possibly adding uncertainty into the creation of bare earth surfaces for China Bar or Pine Bar.

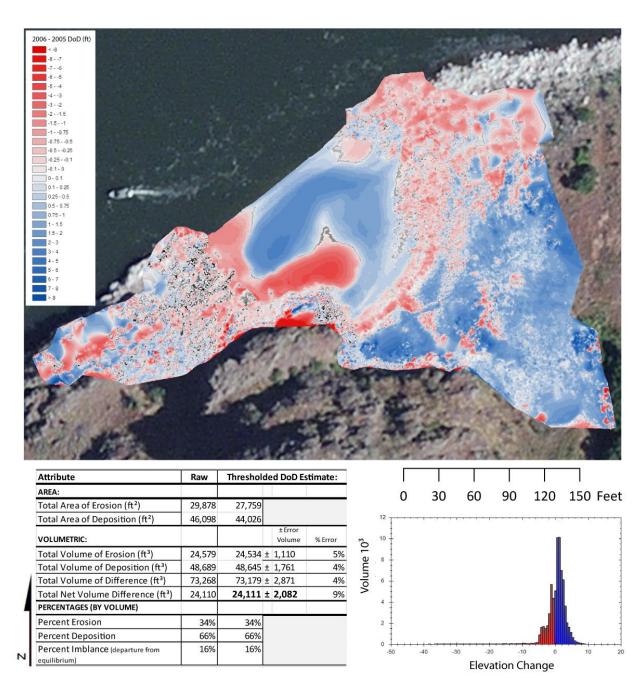


Figure 46 – 2006-2005 DEM of Difference at China Bar using Uniform Estimate of Error of 0.15 ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

SPATIALLY VARIABLE ESTIMATES OF ERROR

Most of the techniques for estimating uncertainty in topographic survey data, as they have been applied in the past, have the aim of collapsing the elevation uncertainty down to a single global metric. However, elevation uncertainty exhibits spatial variability that could exert a strong influence on morphological sediment budget results and interpretations. Given the spatial variability of topographic survey uncertainty, approaches other than uniform estimates of error have been developed. For example, Lodwick and Santos (2003) build terrain models (not of the earth's surface, but it could be applied as such) with fuzzy surfaces. Therein, each elevation of the surface is represented by a fuzzy number and membership function as opposed to a single crisp value. The fuzzy number expresses the range of uncertainty in the elevation values. Similarly, one might represent each elevation in a DEM with its own probability distribution. Fuzzy models may afford some degree of flexibility over probabilistic models.

Chappell *et al.* (2003) used a more traditional geostatistical technique and modeled topography with Kriging surfaces, which explicitly incorporate a spatially variable estimate of uncertainty. An unfortunate by-product of this approach is that it does not preserve the actual surveyed point elevations in the final surface like a simple TIN-based technique. In the case of high-resolution ground-based surveys that specifically capture morphological grade breaks, a Kriging interpolation technique may not work as well as it does on much coarser resolution datasets that are typical in geostatistics.

Although all of these approaches provide a means of expressing elevation uncertainty, neither of these approaches fundamentally provides a mechanism to systematically and robustly quantify the elevation uncertainty. If one is going to revert back to more simplistic spatially uniform estimates of elevation uncertainty, than there is no need to use a complex surface model to represent it. The error budgeting alternative requires inputs that are not readily available and a degree of mathematical numeracy that many geomorphologists and restoration practitioners (primary users of the morphological method) may lack. Thus, a more tractable approach that could estimate spatially variable elevation uncertainty patterns on the basis of readily available information would be preferable.

ROUGHNESS PROXY - DETRENDED STANDARD DEVIATION FROM PC-TOOLS DECIMATION

Detrended standard deviation is a proxy for a surface roughness caused by surface vertical irregularity (Rychkov *et al.*, 2010). Rychkov *et al.* (2010) show empirically that there is a linear dependence between the standard deviation and the grain size, one of the causes of surface roughness. Here we use detrended standard deviation as a proxy for roughness as a stand-alone propagated error surface (Figures 46 and 47) and also as one of three inputs into a Fuzzy Inference System to produce a separate propagated error surface. Removing the local trend of slope from data enables an analysis to focus on the fluctuations in the data about the trend. Using detrended standard deviation as a roughness proxy, we calculated DoDs for each epoch for China Bar and Pine Bar (Figures 48 and 96).

Detrended standard deviation data is an output from the decimation process in PC-Tools and can be found in the '*_zstat.txt' text file (see Page 19-20 for data decimation in PC-Tools).

Steps to create Roughness/Detrended Standard Deviation raster surface:

- In ArcGIS: File → Add Data → Add XY Data...
 - a. Click folder icon and navigate to text (.txt) file to be imported
 - The '*_zstat.txt' text file from the decimation process in PC-Tools is used to build a TIN surface of Roughness

- 1. In the header row of the text files, all dashes (-) must be changed to underscores (_) before bringing text files into ArcGIS
- b. Populate the fields for the X, Y and Z coordinates
 - i. 'stdev_detrended' must be selected from the drop down menu to populate the 'Z field'
- c. Select the coordinate system of the input data by clicking 'Edit..', 'Select...', and navigating to appropriate coordinate system
- d. Click 'OK' and point data is automatically added to ArcGIS Table of Contents
- 2. Create TIN (see Pages 30 to 31)
 - a. In 'height_field' make sure 'stdev_detrended' is selected
- 3. Edit TIN (see Pages 32 to 34)
- 4. Create raster surface from TIN (see Pages 37 to 39)
 - a. This new raster surface is the propagated Roughness error surface used in GCD software
 - b. '.img' must be added to the end of the file name for the file to work in GCD software

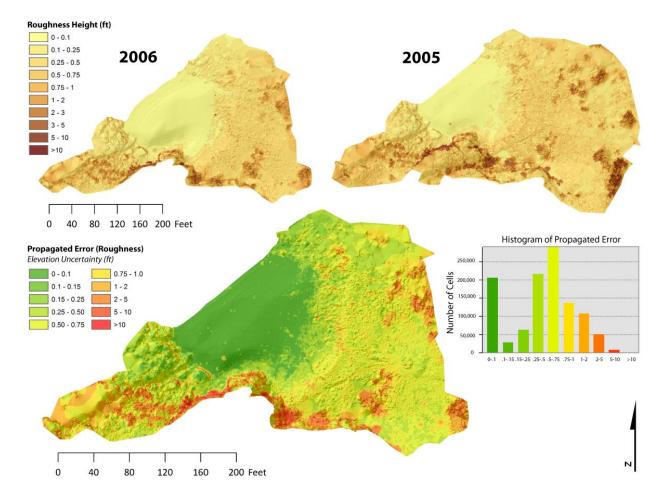


Figure 47 – Propagated error surface produced from 2006 and 2005 roughness rasters for China Bar.

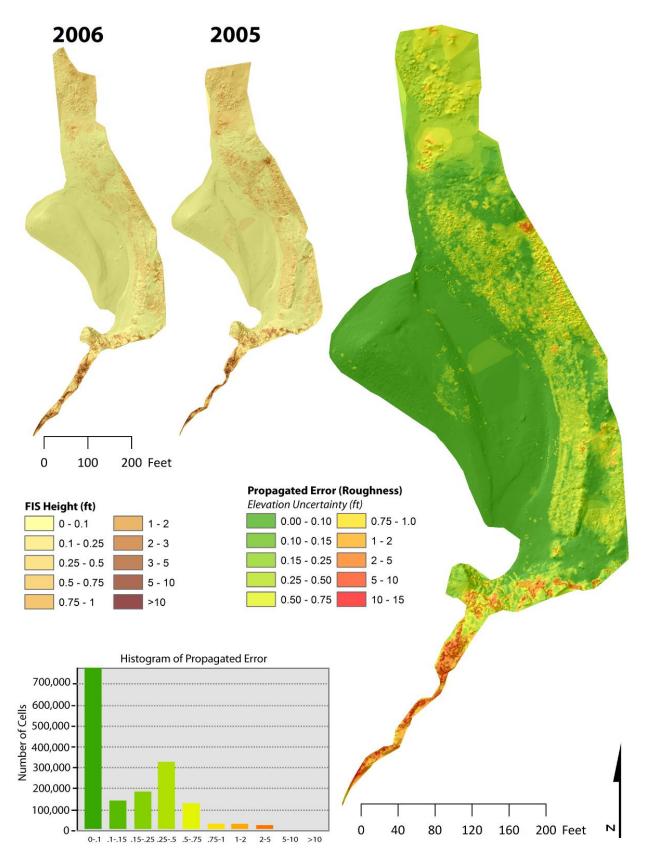


Figure 48 – Propagated error surface produced from 2006 and 2005 roughness rasters for Pine Bar.

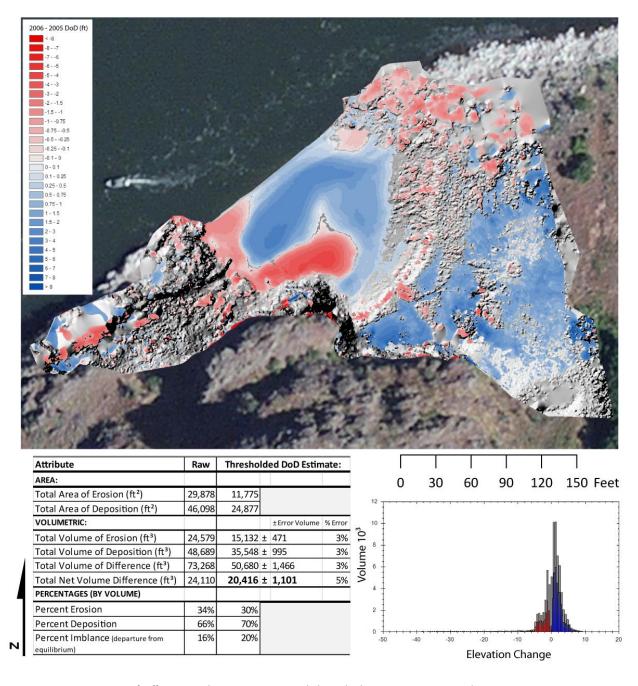


Figure 49 – 2006-2005 DEM of Difference at China Bar using Detrended Standard Deviation as Propagated Error.

TLS FUZZY INFERENCE SYSTEM

Surface representation uncertainties are likely to be spatially variable, not uniform. Therefore, a flexible and robust technique was developed by Wheaton *et al.* (2010) for estimating the magnitude of DEM uncertainty in a spatially variable way using fuzzy set theory. Their approach builds on the conceptual frameworks for uncertainty analysis in the morphological method established by Brasington *et al.* (2000) and Lane *et al.* (2003). Fuzzy inference systems

(FIS) are convenient frameworks for taking the information that is known (inputs) and producing an appropriate output (Jang and Gulley, 2007). In the case of topographic surveys, something is always known about the survey sampling (e.g. point density) and the morphology (slope), and in some cases there may be additional information (e.g. roughness from facies maps, point quality from GPS). The Fuzzy Inference System is a technique that allows more robust estimation of DEM quality and its influence on sediment budgets derived from DEM differencing. Therein, the spatial variability of surface representation uncertainty is considered using a set of tools that could be calibrated and applied to any set of topographic point data.

Although FIS outputs tend not to show significant sensitivity to membership function shape (Klir and Yuan, 1995), fuzzy membership functions come in a wide array of forms, with triangular and trapezoidal membership functions being the most common. The process of defining membership functions can be thought of in two parts. First, the number of linguistic adjectives that could be used to describe each variable needs to be identified. For the inputs used here slope uses the adjectives 'low', 'medium', and 'high', point density uses the adjectives 'sparse', 'medium', and 'dense', and roughness uses the adjectives 'smooth', 'rough', and 'very rough' (Table 2). The second part consists of defining the membership function that describes the range of values covered by each adjective. For the input variables, so long as the membership functions span the range of encountered values for that variable, the exact specification of their membership function is not critical (Jang and Gulley, 2007; Klir and Yuan, 1995). What is more important is that the expert defining the rule system knows what values the adjectives correspond to and develops rules in accordance with those perceptions. For the output variable, the output membership functions must correspond to realistic output values. Although we were able to develop a functional FIS, we are unable to calibrate the FIS to the range of empirically determined values due to the lack of readily available field data to test this. The values used in specification of the input and output membership functions are reasonable, based on other studies, but eventually Idaho Power should do some simple repeat field experiments of a small portion of one or more of their study bars to calibrate these FIS models better.

Rule definition for the FIS is a process of linguistically relating the inputs (using their different adjectives defined above) to a single adjective for the output. For example, if slope is low, point density is dense, and roughness is smooth, then elevation uncertainty is low. By contrast, if slope is high, point density is sparse, and roughness is very rough, then elevation uncertainty is extreme. The complete 3-input rule system used for this FIS is shown in Table 2. A more generic 2-input rule FIS system applicable to any topographic survey based on just slope and point density is reported in Wheaton (2008, Table 4.7).

A fuzzy inference diagram is the standard technique for illustrating how a specific fuzzy inference system operates. Figure 49 shows an illustration of a 2-rule FIS where two examples are shown to contrast the outputs from different point density and slope inputs. The first step in applying the FIS involves the calculation of the output membership function for each applicable individual rule. Not all rules will apply. In the example of Figure 49A only one rule from five candidate rules of the nine total rules applies (i.e. if slope is low and point density high then elevation uncertainty is low). Whereas in Figure 49B, two of six candidate rules of the nine total rules are applicable. Next, the total consequence of all the applicable rules is calculated. This resulting total consequence membership function expresses the full range of uncertainty in the output predicted by the FIS. Finally, if desired, the total consequence membership function can be defuzzified into a single value of elevation uncertainty. To acquire a spatially variable estimate of the uncertainty, the above process is applied on a cell-by-cell basis to the entire raster DEM. To illustrate how this method is conducted for a pairwise DoD calculation, an example from 2006–2005 for each China Bar and Pine Bar are shown in Figures 51 and 52. In Figures 51 and 52 the DEM uncertainty is spatially variable and estimated on a cell-by-cell basis using the FIS.

Table 2 Fuzzy inference system rule set for determining elevation uncertainty based on the three inputs (slope, point density, and roughness).

	Inputs→			Output
Rule	Slope	Point Density	Roughness	Elevation Uncertainty
1	Low	Sparse	Smooth (sand)	Average
2	Low	Medium	Smooth (sand)	Average
3	Low	Dense	Smooth (sand)	Low
4	Medium	Sparse	Smooth (sand)	High
5	Medium	Medium	Smooth (sand)	Average
6	Medium	Dense	Smooth (sand)	Low
7	High	Sparse	Smooth (sand)	High
8	High	Medium	Smooth (sand)	Average
9	High	Dense	Smooth (sand)	Average
10	Low	Sparse	Rough (Gravel/Cobble)	High
11	Low	Medium	Rough (Gravel/Cobble)	Average
12	Low	Dense	Rough (Gravel/Cobble)	Average
13	Medium	Sparse	Rough (Gravel/Cobble)	Extreme
14	Medium	Medium	Rough (Gravel/Cobble)	High
15	Medium	Dense	Rough (Gravel/Cobble)	Average
16	High	Sparse	Rough (Gravel/Cobble)	Extreme
17	High	Medium	Rough (Gravel/Cobble)	High
18	High	Dense	Rough (Gravel/Cobble)	Average
19	Low	Sparse	Very Rough (Boulder/Veg)	Extreme
20	Low	Medium	Very Rough (Boulder/Veg)	Extreme
21	Low	Dense	Very Rough (Boulder/Veg)	High
22	Medium	Sparse	Very Rough (Boulder/Veg)	Extreme
23	Medium	Medium	Very Rough (Boulder/Veg)	Extreme
24	Medium	Dense	Very Rough (Boulder/Veg)	High
25	High	Sparse	Very Rough (Boulder/Veg)	Extreme
26	High	Medium	Very Rough (Boulder/Veg)	Extreme
27	High	Dense	Very Rough (Boulder/Veg)	Extreme

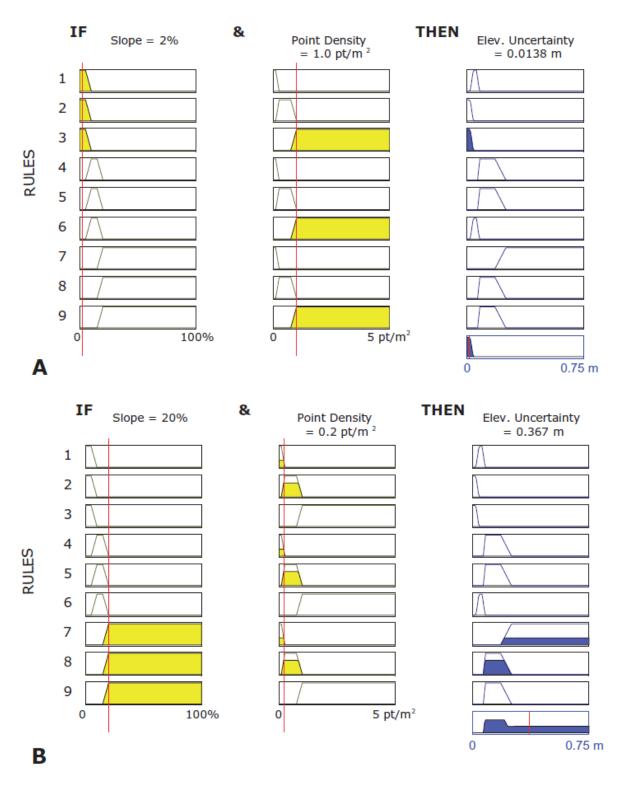


Figure 50 - Two examples of the total consequence of a two input fuzzy inference system. (A) A 'low' elevation uncertainty situation. (B) A 'high' elevation uncertainty situation. In both situations, the total consequence of the relevant rules are aggregated to the shape that appears in the lower right corner. This aggregated fuzzy output is then defuzzified (using a centroid method) to produce a crisp estimate of elevation uncertainty. The thin red vertical lines represent the input values for the two examples. When a rule is applicable, the mass of the membership function it intersects is highlighted yellow. The output membership function is shaded blue but only when it has two applicable inputs.

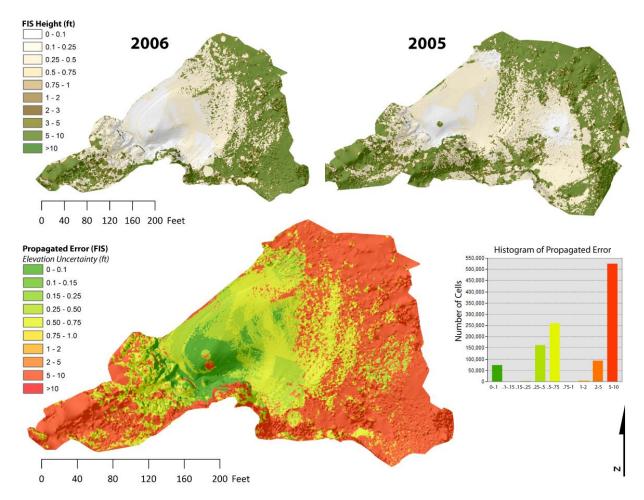


Figure 51 - - Propagated error surface produced from 2006 and 2005 FIS rasters for China Bar.

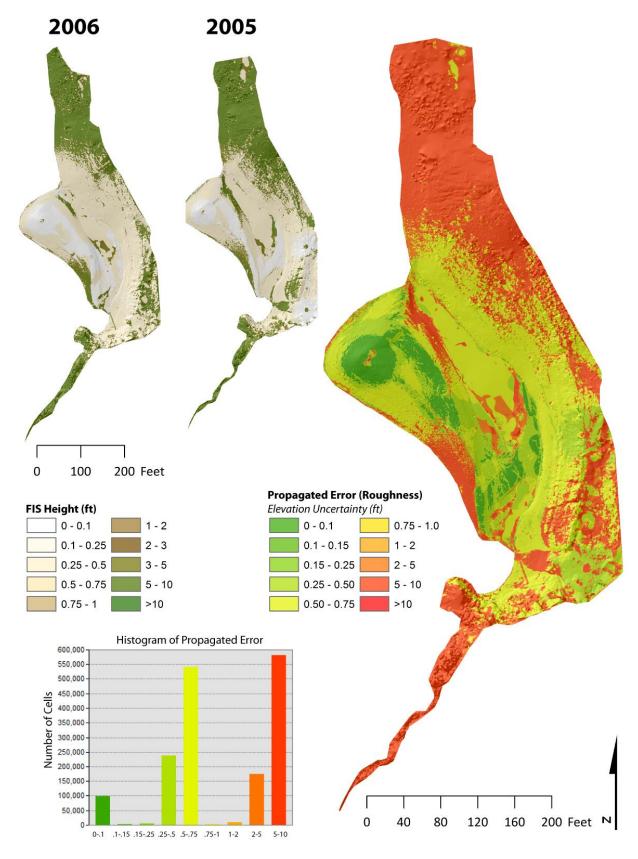


Figure 52 – Propagated error surface produced from 2006 and 2005 FIS rasters for Pine Bar.

A fuzzy inference system was developed and used to estimate the errors in each of the DEMs between 2005 and 2007 at China Bar and Pine Bar on a cell-by-cell basis. Once those errors were established for each DEM, they were propagated through on a cell by cell basis using standard error propagation (square root of the sum of the square of the errors), to establish minimum levels of detection for meaningful change as calculated by the DoD.

Inputs used for the development of the Fuzzy Inference System include 1) Slope (degree), 2) Point Density (pts/ft²), and 3) Roughness/Detrended Standard Deviation.

Slope was calculated using ArcGIS's 3D Analyst, which uses an algorithm that calculates the slope from the center cell to all eight of its surrounding neighbors and then assigns a slope value based on the maximum (i.e. steepest downhill descent).

- 1. Steps to create Slope raster surface:
 - a. In ArcToolbox: 3D Analyst Tools → Raster Surface → Slope; OR, in search window type 'slope', then click 'Slope (3D Analyst)'
 - b. In Slope dialogue box (Figure 52):
 - i. Select DEM raster to perform slope analysis on using dropdown list, clicking on folder icon and navigating to files, or dragging files into 'Input raster' field
 - ii. Select location where to Output raster by clicking on folder icon , name the raster dataset, and click 'Save'
 - 1. '.img' must be added to the end of the file name for the file to work in GCD
 - iii. In Output measurement field select 'DEGREE' from dropdown list
 - iv. Use a Z factor of 1
 - v. Click on 'Environments...', → 'Processing Extent', and navigate to Extents shapefile
 - vi. Click 'OK' (Slope raster automatically added to TOC)

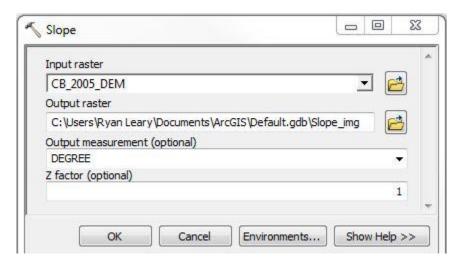


Figure 53 - Dialog box for producing a slope raster from a DEM.

- 2. Steps to create Point Density raster surface:
 - a. In ArcGIS: File \rightarrow Add Data \rightarrow Add XY Data...
 - i. Click folder icon and navigate to text (*.txt) files to be imported

- 1. The '*_zstat.txt' and '*_underpopulated_zstat.txt' text files from the decimation process in PC-Tools are used to build a TIN surface of Point Density
 - a. In the header row of the text files, all dashes (-) must be changed to underscores (_) before bringing text files into ArcGIS
- ii. Populate the fields for the X, Y and Z coordinates
 - 1. 'n' must be selected from the drop down menu to populate the 'Z field'
- iii. Select the coordinate system of the input data by clicking 'Edit..', 'Select...', and navigating to appropriate coordinate system
- iv. Click 'OK' and point data is automatically added to ArcGIS Table of Contents
- b. Create TIN (see Page 30 to 31)
 - i. In 'height_field' make sure 'n' is selected for both files
- c. Edit TIN (see Pages 32 to 34)
- d. Create raster surface from TIN (see Pages 37 to 39)
 - i. This new raster surface is the Point Density raster surface used in the GCD software
 - ii. '.img' must be added to the end of the file name for the file to work in GCD software
- 3. See Pages 49 to 50 for steps to create Roughness surface

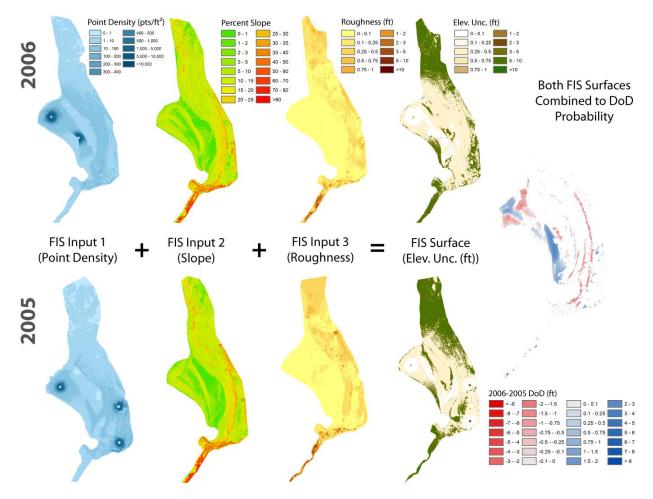


Figure 54 – Illustration of FIS construction and resulting probability map for 2006–2005 DoD from Pine Bar. The top shows the 2006 inputs and the bottom shows the 2005 inputs. The left-hand three inputs combine together as inputs into the three rule FIS to produce the defuzzified FIS prediction of elevation uncertainty. Both predictions of elevation uncertainty combine to produce the probability map that DoD changes are real.

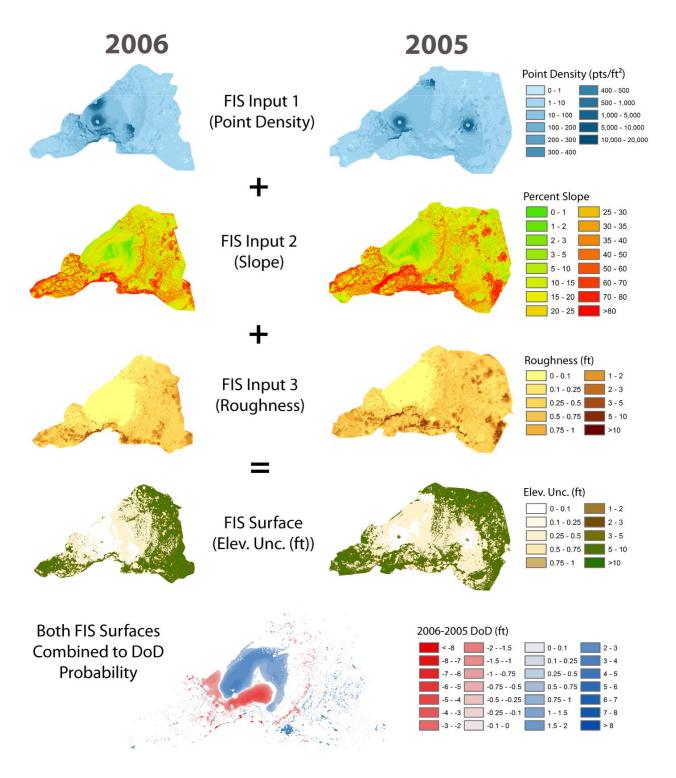


Figure 55 – Illustration of FIS construction and resulting probability map for 2006–2005 DoD from China Bar. The left figures show the 2006 inputs and the right figures show the 2005 inputs. The top three inputs combine together as inputs into the three rule FIS to produce the defuzzified FIS prediction of elevation uncertainty. Both predictions of elevation uncertainty combine to produce the probability map that DoD changes are real.

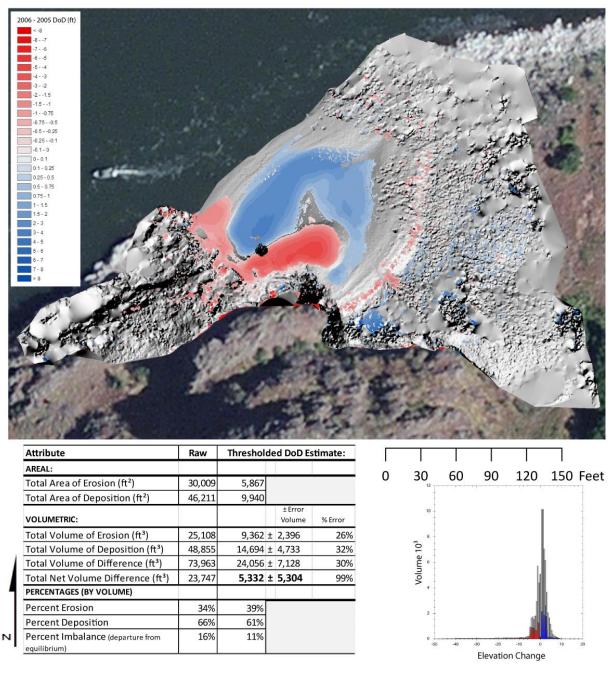


Figure 56 – 2006-2005 DEM of Difference at China Bar using the Fuzzy Inference System as Propagated Error.

SUMMARY

Here, the significance of propagated DEM uncertainty into uncertainty in DoD predicted elevation changes are presented three ways: 1) simple minimum level of detection; 2) uniform estimates of error; and 3) spatially variable estimates of error. The minLoD (0.15 ft) and uniform estimate of error (0.15 ft) values used for China Bar and Pine Bar DoDs were values that closely represented the error associated with the equipment used during data collection. The spatially variable estimates of error include two different methods: roughness proxy/detrended standard deviation and the application of a Fuzzy Inference System (FIS).

Regardless of the approach used, the process of accounting for DoD uncertainty follows a consistent progression through three steps:

- Quantifying the surface representation uncertainty in the individual DEM surfaces that are being compared;
- 2. Propagating the identified uncertainties into the DoD;
- 3. Assessing the significance of the propagated uncertainty.

The end goal is to propagate the estimated uncertainty in two DEMs into a DoD, to differentiate between those DoD calculated changes such that confidence can be developed in distinguishing changes due to geomorphic processes from changes due to "noise". Wheaton *et al.* (2010) and Wheaton (2008) describe in more detail than presented here methods for accounting for uncertainties in DEMs.

CHANGE DETECTION (DEM DIFFERENCING)

Repeat topographic surveys are often used to monitor geomorphic change in rivers. The process of estimating geomorphological change from repeat topographic surveys has come to be known as the morphological method. The DEM of Difference (DoD) version of the morphological method involves the simple mathematical operation of subtracting the elevations in the older surface from the elevations in the newer surface. This can be converted to a volumetric estimate of change by multiplying the calculated elevation change in each grid cell by the grid resolution (area) and summed as desired to compare deposition and erosion.

Digital elevation models derived from each survey are differenced to produce DEMs of difference (DoD). DoDs are used to estimate the net volumetric change in a reach through time (see Figure 57). From a geomorphic perspective, these represent the change in storage terms (due to erosion and deposition) of a sediment budget.

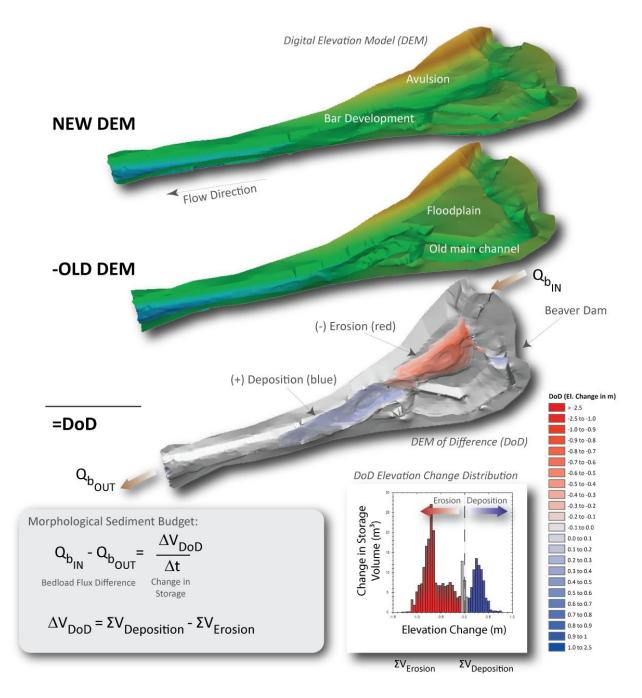


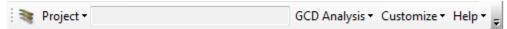
Figure 57 – Concept of DEM differencing.

From each change detection analysis between 2005 and 2007 at Pine Bar and China Bar, we calculated the total area of deposition, total area of erosion, net volume difference, total volume of deposition, total volume of erosion, and total volume of difference (see Appendix B). The net volume difference is simply the difference between erosion and deposition and indicates whether a reach is experiencing net aggradation (when positive) or degradation (when negative) or is in approximate equilibrium (roughly zero). We also plotted elevation change

distributions and the thresholded DoDs for each change detection analysis (see Appendix B). We used the Geomorphic Change Detection Software version 5 to do these analyses (http://gcd.joewheaton.org).

STEPS REQUIRED FOR A GEOMORPHIC CHANGE DETECTION (GCD) ANALYSIS

- 1. Download and install GCD software
- 2. In ArcGIS add Geomorphic Change Detection toolbar:



- 3. Create a New GCD Project
 - a. In GCD toolbar create a New Project by clicking 'Project' → 'New...'
 - i. Name the GCD Project
 - ii. Select folders where GCD files will be stored
 - iii. GCD Project is automatically added to GCD toolbar
 - iv. It is recommended that a new GCD Project be created for each site (e.g. China Bar)
- 4. Add files into Survey Library
 - a. In GCD toolbar click 'GCD Analysis' → 'Survey Library'
 - b. GCD version 5.0 allows raster surfaces to be input without having the same extents or exact same survey area or overlap. In previous versions of GCD software steps needed to be taken to ensure that the two surveys being used to calculate a DoD had the same overlap (i.e. Calculate raster domains, intersect them and output overlap, and extract by mask for DEMs that are of the exact same shape and size).
 - c. Add all DEM surfaces that will be used for a GCD analysis at a particular site (Figure 58)
 - Each DEM surface is analogous to an individual survey of a site (e.g. 'CB_06vs05_2005' is the China Bar 2005 DEM and associated surfaces that have the same shape as the 2006 DEM and associated surfaces)

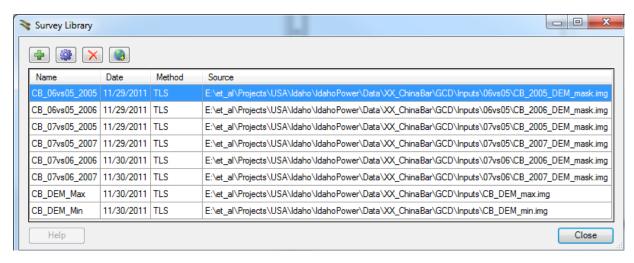
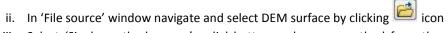


Figure 58 – Survey Library in GCD software showing all DEMs used for Geomorphic Change Detection at China Bar.

- d. In Survey Library click icon to add an individual DEM surface (Figure 59)
 - i. Name and date DEM surface



- iii. Select 'Single method survey' radial button and survey method from the drop down menu (TLS in this case). Note that, multi-method surveys are allowed, but as of GCD 5.0.36, ony one FIS per multi-method is allowed. This will be modified in the future to allow multiple FIS models in mulit-method (e.g. one FIS model for TLS, one for total station, and one for MBB).
- e. In 'DEM Survey Properties' dialog box click the 'Associated Surfaces' tab to add the Point Density, Slope Analysis, and Roughness raster's associated with the particular DEM surface (Figure 60)
 - i. Click the icon to add an associated raster surface
 - 1. Name the surface (e.g. 'CB_2005_SA' for 2005 Slope Analysis at China Bar)
 - 2. Click icon to navigate to surface
 - 3. Select the surface type from 'Type:' drop down menu
- f. In 'DEM Survey Properties' dialog box click the 'Error Calculations' tab to add Error raster surfaces (Figure 60). Click the icon to add new error surfaces, here we create three:
 - i. Uniform Error
 - 1. To calculate Uniform Error
 - a. Click icon to bring up 'Error Properties' dialog box
 - b. Name the error surface that is being created
 - c. Select 'Uniform Error' as Error Type
 - i. Method should be TLS with an Error Value of 0.15
 - ii. Click 'OK'
 - ii. Detrended Standard Deviation as a proxy for surface roughness
 - When using versions of GCD prior to version 5.0, one will need to "fool" GCD by
 creating an error surface using the same steps as a uniform error surface and
 then go into the file structure (works best in ArcCatalog) and over write the
 newly created error surface with the detrended standard deviation raster
 surface. Is this going to get fixed, since as of now it does not work.
 - iii. Fuzzy Inference System (FIS)
 - 1. Load FIS file into FIS Library
 - a. In GCD toolbar click 'Customize' → 'FIS Library'
 - b. Click icon to add new FIS
 - c. In 'Add FIS Library File' dialog box click icon and navigate to FIS
 - d. Name the file in 'Name:' field
 - e. Click 'OK' and FIS is added to library
 - 2. Click icon to bring up 'Error Properties' dialog box
 - 3. Name the error surface that is being created (e.g. something like 'CB_2005_FIS' for the 2005 FIS error surface at China Bar)
 - 4. Select the FIS file that was added to the FIS library as the Error Type
 - 5. Method should be TLS with an Error Value of 0.15

- 6. Add the Associated Surfaces needed for the FIS to work (here it is Slope, Point Density, and Roughness)
- 7. Click 'OK'
 - a. It may take a while (up to 15 minutes) for the FIS raster surface to be created

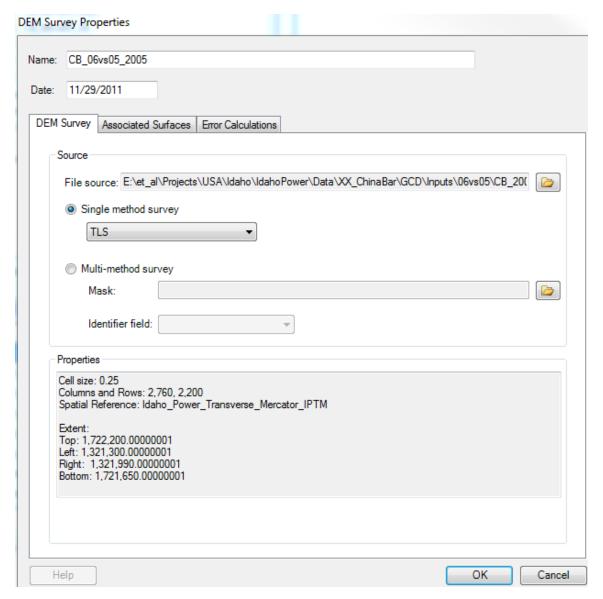


Figure 59 – Dialog box in Survey Library for a particular DEM surface / survey.

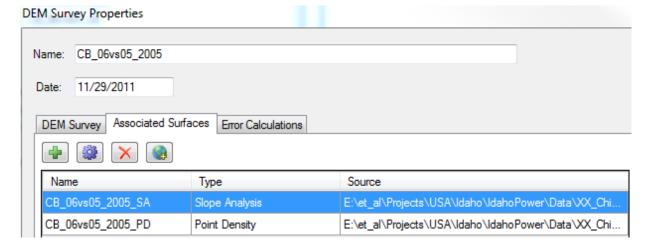


Figure 60 - Dialog box in Survey Library for Associated Surfaces with a particular DEM surface / survey.

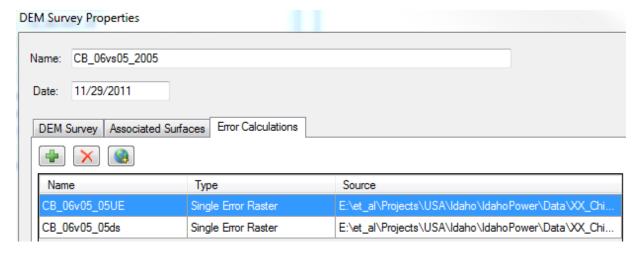


Figure 61 – Dialog box in Survey Library for Error Calculations with a particular DEM surface / survey.

- 5. Calculate a Change Detection Analysis
 - a. In GCD toolbar click 'GCD Analysis' → 'Change Detection'
 - b. Name the Change Detection
 - i. Use something descript that will distinguish different change detections analyses
 - c. Inputs
 - i. Select the DEMs that the GCD will be calculated on using the 'New Survey' and 'Old Survey' drop down menus (notice all the DEMs loaded in the Survey Library appear in each drop down menu). The new survey should always be a more recent survey than the old survey.

- ii. For all Change Detection calculations except 'Simple minimum level of detection', error surfaces will be selected using the 'New Error' and 'Old Error' drop down menus and applied by clicking the 'Propagated errors' or 'Probability' radial button.
 - 1. There are three types of propagated Error surfaces presented
 - a. Uniform Error
 - i. See Page 47 to 48 & 65 for description and how produced
 - b. Detrended Standard Deviation as a proxy for roughness
 - i. See Page 49 to 50 for description and how produced
 - c. Fuzzy Inference System (FIS)
 - i. See Page 52 to 60 & 65 for description and how produced

d. Uncertainty

i. Check the 'Simple minimum level of detection' radial button when calculating a GCD with no surface uncertainty. After the GCD is calculated, a threshold can be manually



applied using the slide on the right side of the histogram

(see Figure 61).

- ii. Check the 'Propagated errors' radial button to apply error surfaces selected in the 'New Error' and 'Old Error' drop down menus
- iii. Check the 'Probability' radial button to apply a confidence level to a GCD calculation.
- e. When Inputs and Uncertainty have been chosen click 'Calculate' to run the GCD
 - i. Temporary DoD files added to ArcGIS Table of Contents (TOC)
 - ii. Outputs Histograms
 - 1. Two histograms are produced, volume and area (choose by clicking appropriate radial button)
 - 2. Each histogram is automatically output to its appropriate Change Detection folder.
 - iii. Outputs Statistics
 - 1. The statistics summary table is automatically output to its appropriate Change Detection folder.
 - iv. Outputs DEM of Difference (DoD)
 - 1. To save the DoD click the 'Save' button
 - a. DoD is automatically added to TOC in ArcGIS and a folder with DoD files is created under folder specified in Step 3.a.ii (Figure 64).
 - b. Temporary DoD files created in TOC can be deleted after saved DoDs are added to TOC

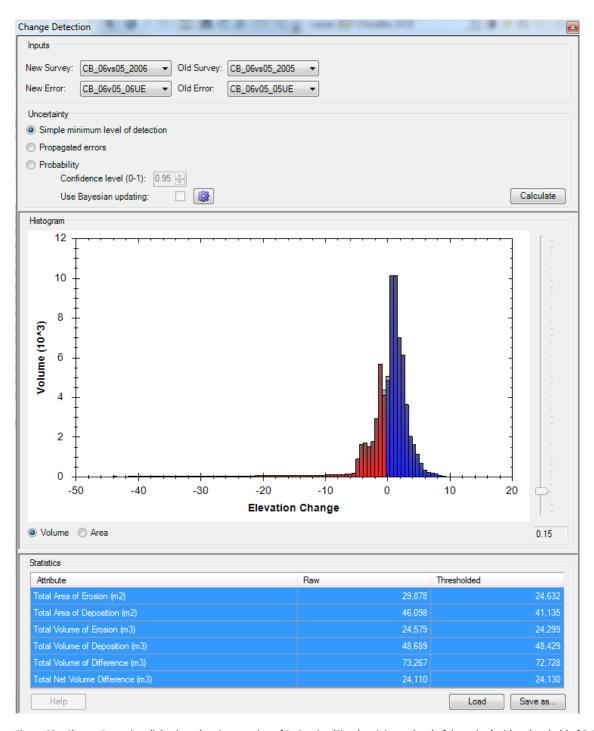


Figure 62 – Change Detection dialog box showing creation of DoD using 'Simple minimum level of detection' with a threshold of 0.15 ft.

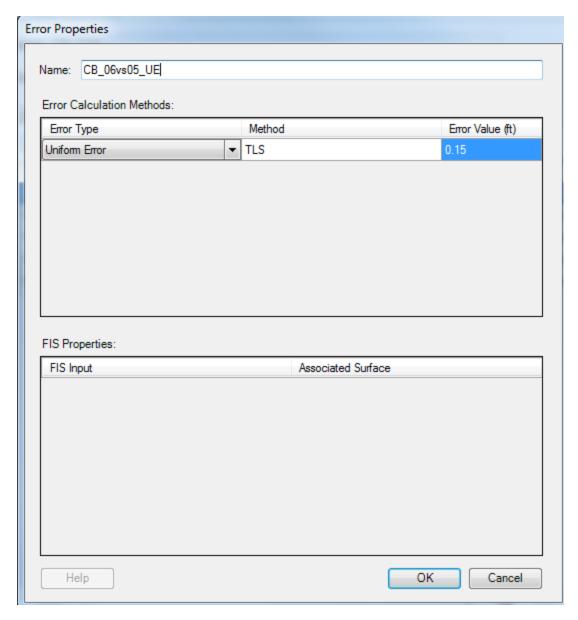


Figure 63 – Dialog box for calculating Uniform Error as a propagated error surface.

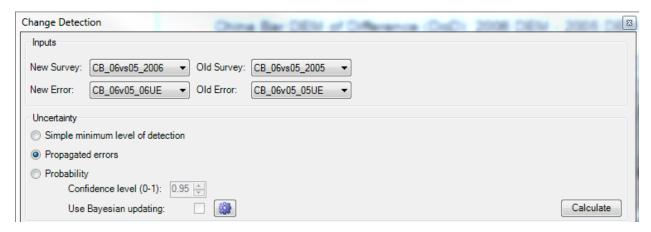


Figure 64 – Geomorphic Change Detection software dialog box showing creation of DoD using propagated error with uniform errors.

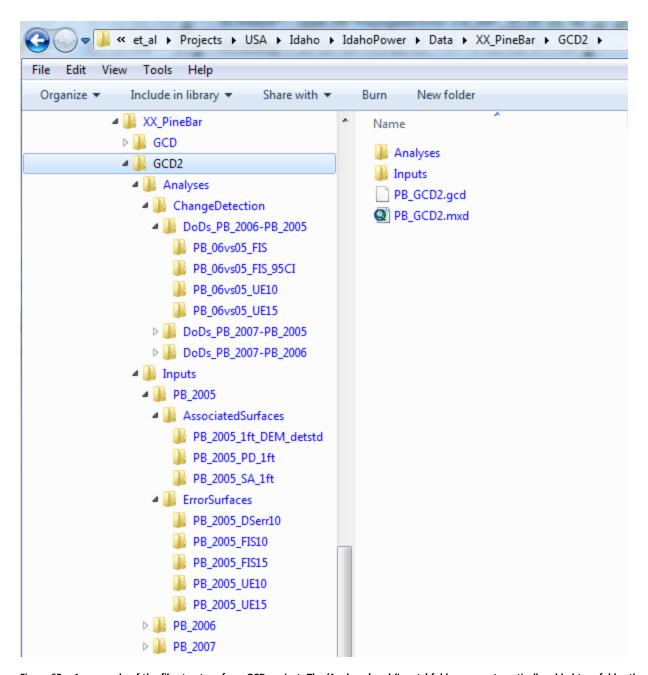


Figure 65 — An example of the file structure for a GCD project. The 'Analyses' and 'Inputs' folders are automatically added to a folder the user specifies when a GCD project is created. Subsequent folders are automatically added to the 'Inputs' folder when layers are added or created in the Survey Library and subsequent folders are automatically added to the 'Analyses' folder when Change Detection analyses are saved.

BUDGET SEGREGATION & INTERPRETATION

To provide a more robust understanding of how elevation changes are organized spatially, we can segregate the DoD budget by different attributes such as flow, surface roughness, and elevation, the DoD can be segregated by different groupings of these values. In Figure 65, China Bar was divided into two groups: the sandbar and areas outside the sandbar. The changes revealed in the DoD are segregated based on these groupings and the geomorphic change occurring in each group is presented separately for each group. In addition to providing unique summaries of change for each group this also allows the user to determine if there is more change occurring in particular groupings.

Budget segregation groups can be created from any number of spatial parameters and are actualized by representing the groupings in a shapefile in ArcGIS and GCD. For example In Figure 65 a polygon was drawn around the area established as the sandbar as well as the area established as being outside of the sandbar and both were saved to a polygon shapefile.

Budget segregation is a powerful tool in geomorphic change detection interpretation, a user can segregate the geomorphic change in any way they see fit, examples of possible ways to segregate a budget are: defined spatial boundaries (sandbar/outside sandbar), flow bands, elevation and surface roughness. Examples of these are presented in Figures 65 through 68.

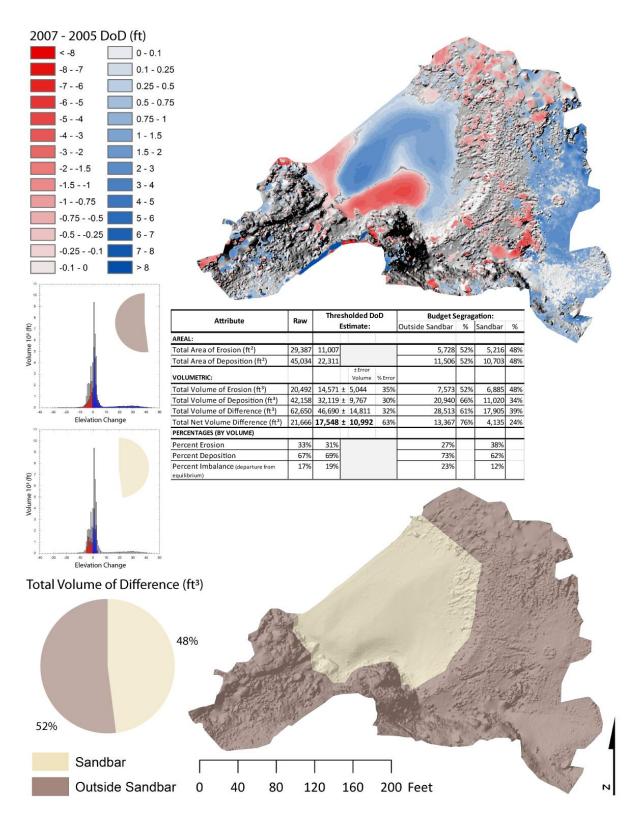


Figure 66 —Budget Segregation example from China Bar study site using the sand bar and areas outside the sandbar to distinguish areas of segregation. Sandbar shapefile was applied to Detrended Standard Deviation as Propagated Error DEM of Difference. Histograms show erosion and deposition distributions for each area. Table shows areal and volumetric changes for thresholded DoD and the amount partitioned into the sandbar and areas outside the sandbar.

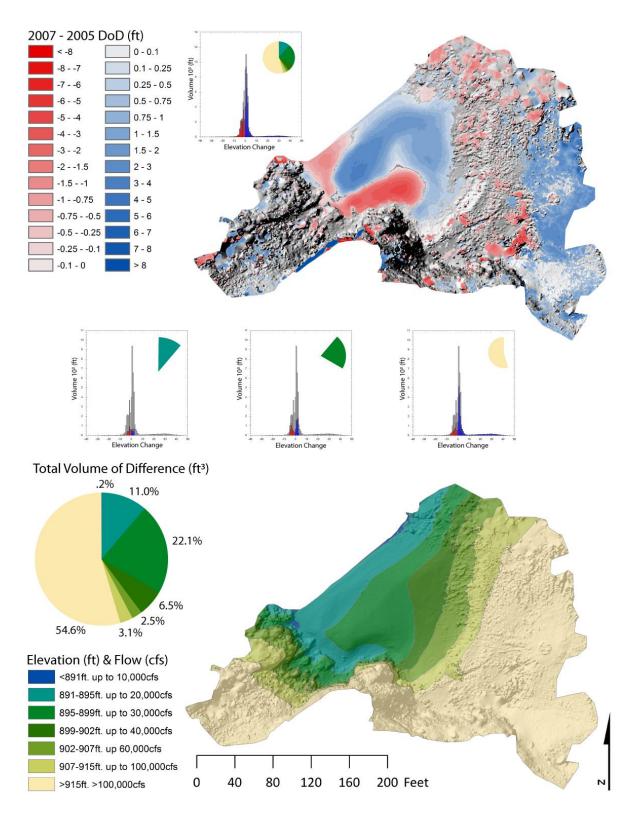


Figure 67 –Budget Segregation example from China Bar study site using flow bands to distinguish areas of segregation. Flow bands shapefile was applied to Detrended Standard Deviation as Propagated Error DEM of Difference. Histograms show erosion and deposition distributions for a specific flow band.

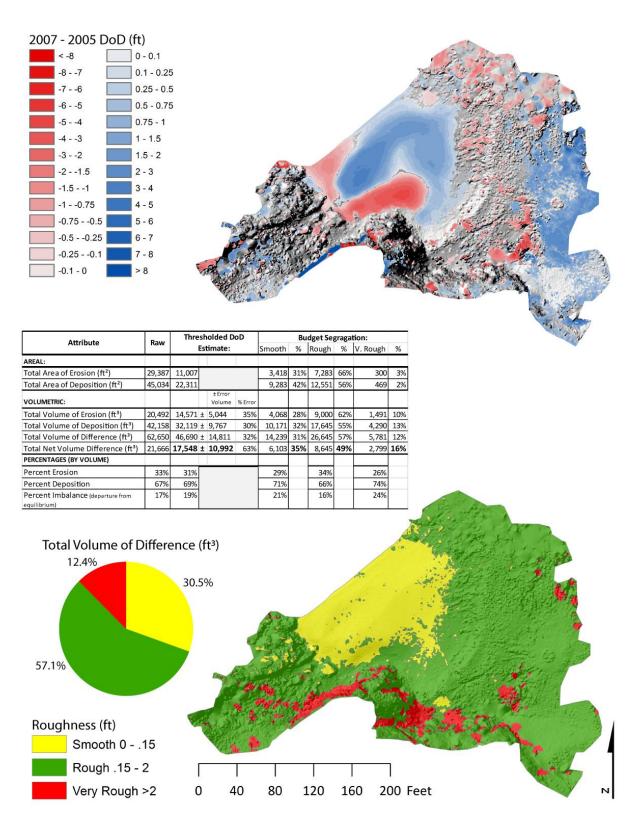


Figure 68 – Budget Segregation example from China Bar study site using roughness categories to distinguish areas of segregation. Roughness categories shapefile was applied to Detrended Standard Deviation as Propagated Error DEM of Difference. Table shows areal and volumetric changes for thresholded DoD and the amount partitioned into each roughness category.

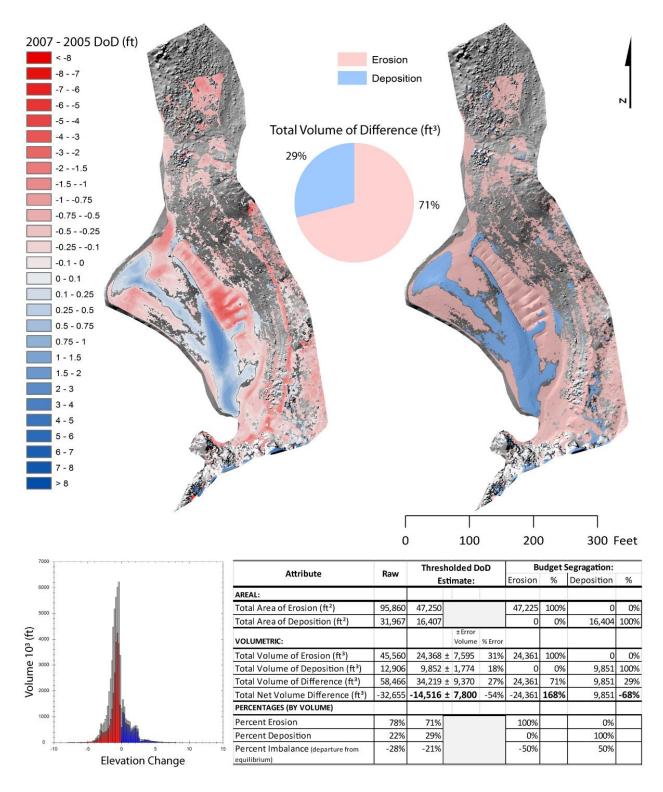


Figure 69 – Budget Segregation example from Pine Bar study site using areas of erosion and deposition to distinguish areas of segregation. Erosion/Deposition shapefile was applied to Detrended Standard Deviation as Propagated Error DEM of Difference. Table shows areal and volumetric changes for thresholded DoD and the amount partitioned into depositional and erosional areas.

SUMMARY OF TLS CHANGE DETECTION WORKFLOW RECOMMENDATIONS

Surveying Recommendations:

- The survey extent of TLS data should be *roughly* consistent from year to year. Geomorphic change detection can only be performed on areas that have the same input extent. Keeping a consistent extent ensures that the change detection can be performed consistently over the same areas. As is shown in Figure 4 the larger survey extent of the 2007 survey does not provide more information in a geomorphic change detection study unless the same extent is also used in the following year's surveys.
- Areas of high surface roughness and large amounts of vegetation pose problems for TLS surveys and may
 be better surveyed by augmenting these areas with a TS survey. To ensure that the maximum area is
 surveyed, TLS surveys should be performed in autumn during low flows. Additionally bar areas being
 covered by water during the time of survey should be supplemented with an alternative surveying
 technique, TS or multi-beam SONAR, this will include important eddy complexes that would not otherwise
 be included in the change detection if a survey using only TLS is performed.

Post Processing:

- Post processing of TLS data should be performed in software of the manufacturer of the scanner used to acquire the data. Since Idaho Power has been using Leica Scan Stations, in this case that software is Leica's Cyclone software.
- To save contractor time and IPC money, legacy data should be registered in Idaho Power Coordinate System (or whatever coordinate system IPC prefers to work in) before data is cleaned in post processing software. All future surveys should be done in the Idaho Power Coordinate System. Cyclone 7.1 software should be used to transform all legacy scans onto the same coordinate system as the control and TS data. Next, undesirable points in the scan data need to be manually filtered including boats, people, survey equipment, vegetation, and other features that do not represent the landscape. To facilitate use of the point cloud data in other point cloud software, the point clouds should be exported for each reach by year into a *.pts format, which is a generic ASCII point cloud format. A detailed workflow for using Cyclone 7.1 post processing software is presented in pages 12 to 18.
- To better manage the large file sizes and point densities of TLS point clouds the use of PC-Tools should be used to decimate the point clouds. A decimation process serves many purposes mainly: to make the dataset more manageable to deal with, derive statistical models of error, derive bare earth and roughness approximations, and explore options of the raster cell size used in the analysis. A detailed workflow for how to utilize PC-Tools for these purposes is given on pages 18 to 26.

DEM Construction:

Using minimum elevation, a Triangulated Irregular Network (TIN) should be used to convert decimated
point clouds to the raster DEM used in the analysis. Once a TIN has been created it is important to
edit/remove areas that have interpolated over large distances, an example of this is shown in Figure 31.
 Specific instructions on creating and editing TINs from a point cloud and converting these to raster format

are given on pages 27 to 38. A shapefile designating the extent of analysis should be created and used to ensure that all rasters being used in the analysis are concurrent.

Error Modeling:

- Before differencing DEM, an error estimation for each survey should be created. A variety of methods
 have been presented in this report: simple minimum level of detection, uniform estimate of error, and a
 spatially variable model. When choosing an error model a number of important factors should be
 considered: quality of survey data, accuracy required of reported geomorphic change, and user's
 knowledge of survey technique and the impact of spatial parameters on the accuracy of the surveying
 technique. In general, the simplest most conservative technique should be used that will facilitate the
 analysis. If that method proves to conservative and inadequate for detecting changes, a more
 sophisticated error model should be used.
- Considering the high accuracy of TLS data, high accuracy required of geomorphic change reporting for IPC, and the expert knowledge of IPC staff of the surveying techniques and river reaches being surveyed, a spatially variable error model is the most appropriate for IPC. Slope, point density, and roughness rasters are the recommended input for a Fuzzy Inference System (FIS) to determine the error associated with each cell in a DEM surface. Raster surfaces of point density and surface roughness are derived from the output point outputs of PC-Tools, while slope is derived from the DEM surface of a survey. A specific workflow for calculating these surfaces as well as an FIS is given on pages 49 to 59.

Change Detection:

- Regardless of the approach used, the process of accounting for DEM of Difference (DoD) uncertainty follows a consistent progression through three steps:
 - 1. Quantifying the surface representation uncertainty in the individual DEM surfaces that are being compared;
 - 2. Propagating the identified uncertainties into the DoD;
 - 3. Assessing the significance of the propagated uncertainty.
- The end goal is to propagate the estimated uncertainty in two DEMs into a DoD, to help differentiate
 between those DoD calculated changes that are thought to be real versus those that cannot be
 distinguished from noise.
- Geomorphic Change Detection Software (GCD) provides the user with a set structure for applying all three of the error propagation models presented in this report and is the recommended software to perform geomorphic change detection analysis with. A detailed workflow of how to use GCD for all 3 methods is given on pages 64 to 72.

SUGGESTED AREAS OF FUTURE WORK

For Idaho Power Company's geomorphic monitoring needs in Hells Canyon, the most pressing two needs are i) working through the back-log of legacy data, and ii) improving the efficiency and workflows of ongoing data collection efforts so that as data comes in, IPC can keep up with processing and interpreting data as it comes in. With regards to TLS change detection of sand and gravel bars in Hells Canyon, we recommend:

1. Processing the back-log of existing data identified in this report to put it all into Idaho Power Coordinate System, and employ the change detection methods outlined in this report. All existing data should be

- used to look for trends within and between sites with respect to morphological sediment budgeting, dominance of different fluvial processes and site specific issues.
- 2. Once an analysis, interpretation and synthesis of all existing TLS data is complete, develop some hypotheses about the geomorphic behavior at each of these bars and adjust monitoring campaigns to put IPC in a position to better test those hypotheses. If appropriate, flow experiments could be used to test explicit hypotheses about bar response to certain flow prescriptions.
- 3. Provide clear guidance to IPC contractors responsible for future TLS data collection as outlined in this report, and insist that deliverables are provided in a manner that allows for quick analysis. As part of this, we highly recommend augmenting TLS surveys with total station surveys of breaklines along banks and vegetated areas and wadeable bathymetry.
- 4. Conduct some simple field experiments to better calibrate error models recommended in this report.
- 5. Invest in some tool and software development to streamline some of the workflows for processing existing data, ingesting new data as it comes in and staying on top of the analysis.
- 6. Keep on top of developments and advancements in TLS monitoring and geomorphic change detection as it is rapidly evolving and periodically adapt monitoring and analysis campaigns appropriately to benefit from such advances and improve efficiency.

Beyond the TLS-specific recommendations, we suggest the integration of these data collection, analysis and synthesis with other ongoing monitoring efforts (e.g. Multi-Beam Bathymetric Surveys) in Hells Canyon.

CONCLUSIONS

The workflow and methods presented in this report demonstrate tractable workflows for processing and analyzing TLS data based on accepted principles of geomorphic change detection. The methods presented exceed the standards of practice of many researchers and practitioners, but ensure confidence in the analysis. The workflows suggested can do nothing to 'fix' erroneous data or extend existing datasets to spatial extents that were not surveyed nor to times when no snap-shot was taken. What they do instead is facilitate a transparent and defensible analysis of what geomorphic changes can be interpreted from the data and distinguished from noise. In general, the analysis permits a very high degree of confidence in the spatial changes and where detectable, discernible changes have taken place. Similarly, the volumetric estimates of these changes in terms of erosion and deposition are reasonable, and can be summed to come up with quite reasonable estimates of total change (a metric of dynamism, turnover and change in sediment storage). However, interpreting net changes (deposition erosion) can frequently produce indeterminate results (where the net change is less than the volumetric uncertainty). Such indeterminate results either mean that the area of interest is in dynamic equilibrium or that the differences between erosion and deposition are not large enough to discern a aggradational or degradational trend larger than noise. This is a very common result. However, when net change results produce do produce a significant difference (i.e. net change is greater than propagated volumetric error), this is a result one can be very confident in for that epoch and area of interest. Statistically robust change detection methods reveal the kinematics of geomorphic change, and can be used for generating and testing mechanistic hypotheses about how these features are evolving through time and in response to different flows. However, explaining the causes definitively can be done with more confidence when augmented with complimentary field methods.

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APPENDIX A: DATA STORAGE

The data used in this report are all archived and backed up and hosted in a secure private portion of the ET-AL server. IPC also hosts duplicate copies of the raw data provided to ET-AL. After the change detection analyses are finalized based on these data, processed point clouds and output products will be delivered to Idaho Power on the external hard-drive that was provided to ET-AL from IPC.

APPENDIX B: GEOMORPHIC CHANGE DETECTION ANALYSES 2005-2007

In this appendix we present the preliminary change detection analyses performed at China Bar and Pine Bar. Shown are both unthresholded DoD budgets (no uncertainty analysis) and DoD budgets with a propagated error as a probability threshold. The appendix is organized by reach, years compared, and geomorphic change detection method (example below).

China Bar

2006-2005 DoD Analysis

Simple Minimum Level of Detection Thresholded at 0.15 ft.

Uniform Error as Propagated Error

Uniform Error as Propagated Error, Probabilistically Thresholded at 95%

Detrended Standard Deviation as Propagated Error

Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%

Fuzzy Inference System as Propagated Error

Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%

2007-2005 DoD Analysis

2007-2006 DoD Analysis

2005 through 2007 Transient Storage Analysis

Simple Minimum Level of Detection Thresholded at 0.15 ft.

Propagated Error with Uniform Errors

Propagated Error with Uniform Errors, Probabilistically Thresholded at 95%

CHINA BAR

2006-2005 DOD ANALYSIS

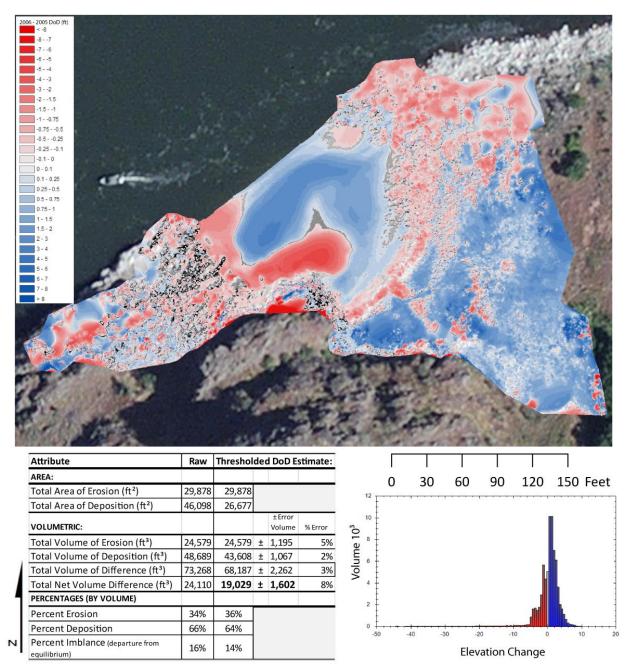


Figure 70 – DEM of Difference using Simple Minimum Level of Detection Thresholded at 0.15 ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

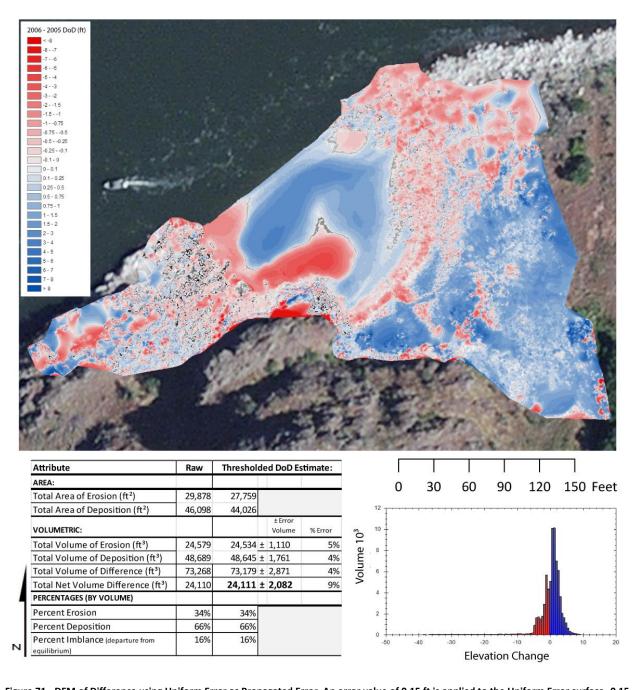


Figure 71 - DEM of Difference using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

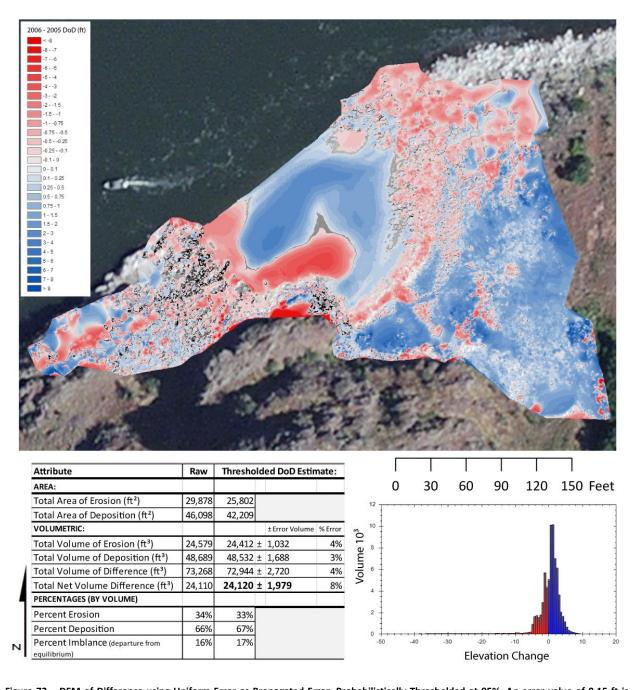


Figure 72 – DEM of Difference using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

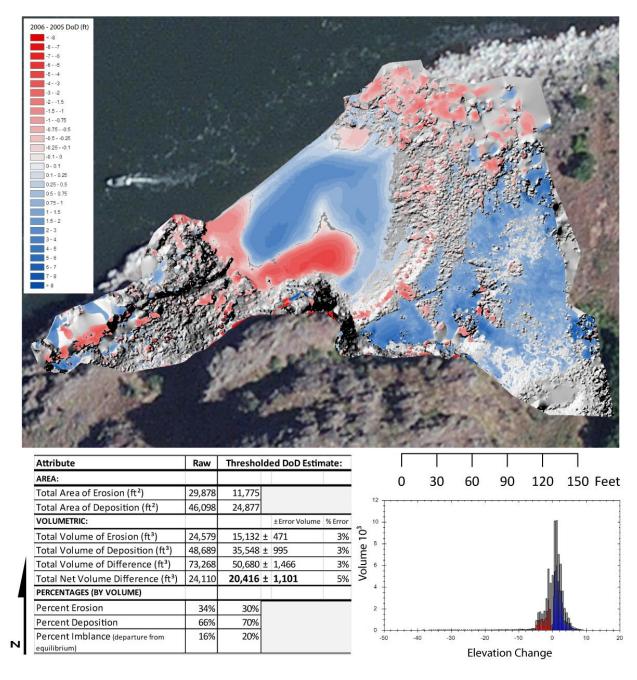


Figure 73 – DEM of Difference using Detrended Standard Deviation as Propagated Error.

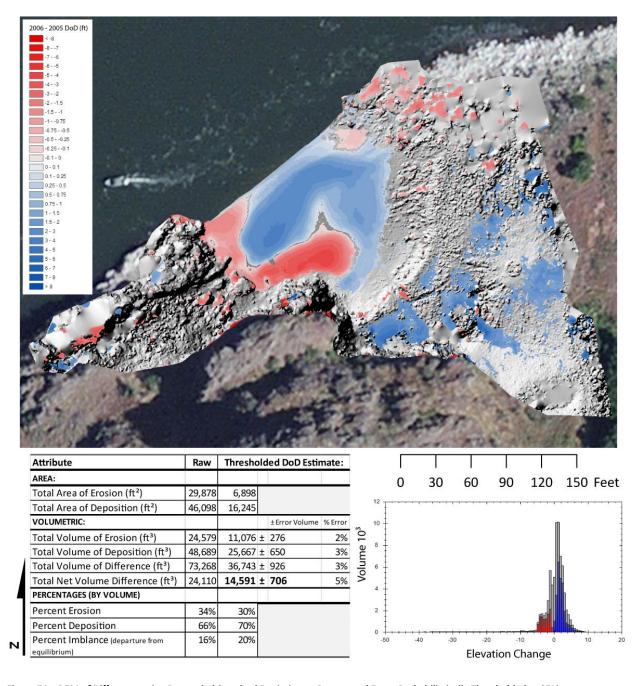


Figure 74 – DEM of Difference using Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%.

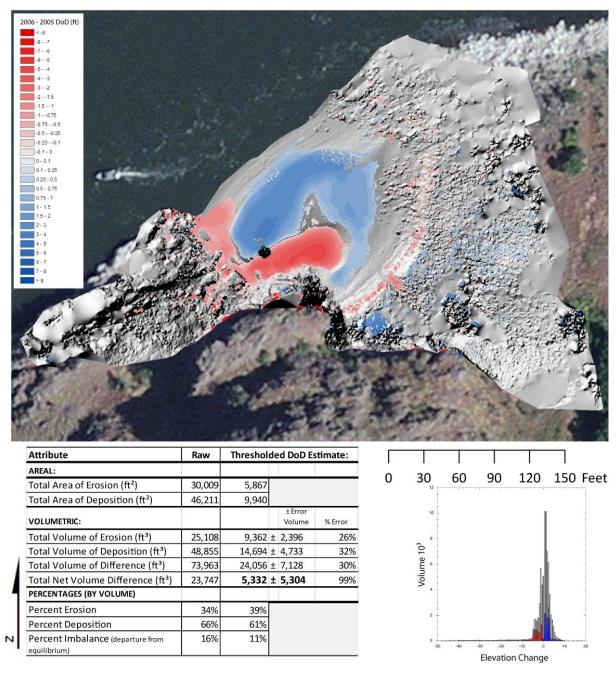


Figure 75 – DEM of Difference using the Fuzzy Inference System as Propagated Error. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

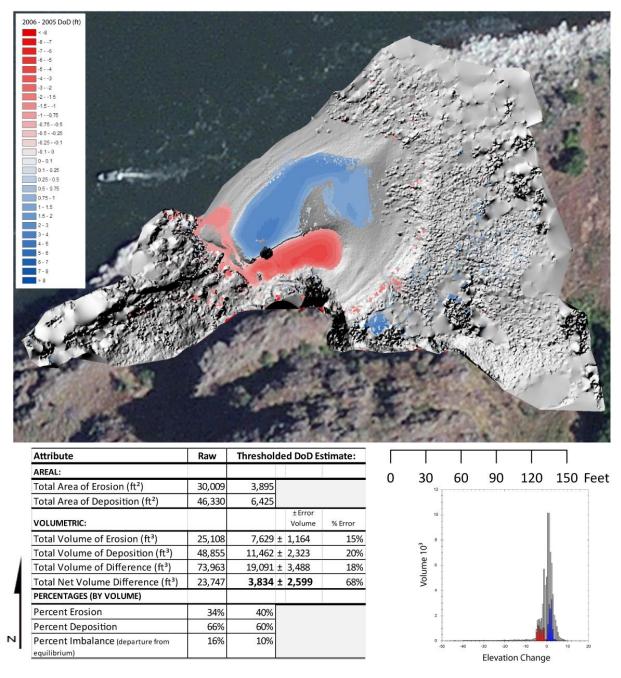


Figure 76 – DEM of Difference using the Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

2007-2005 DOD ANALYSIS

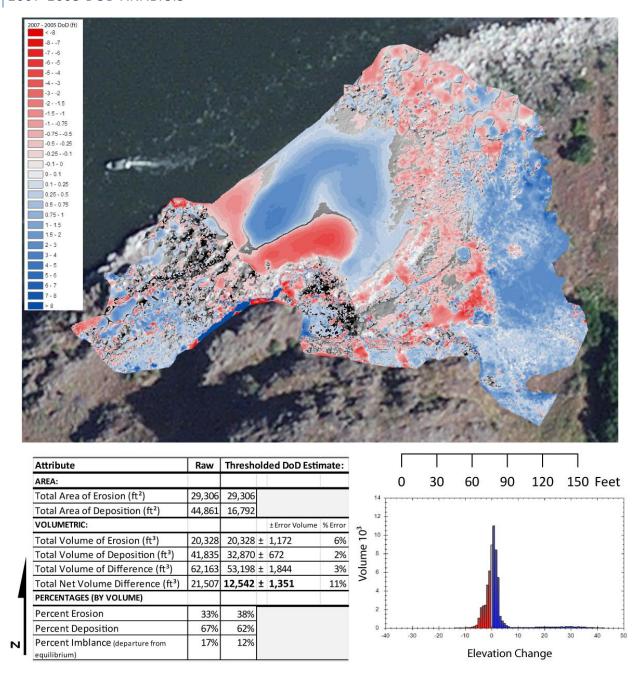


Figure 77– DEM of Difference using Simple minimum Level of Detection Thresholded at 0.15 ft is representative of the error associated with the equipment used during data collection.

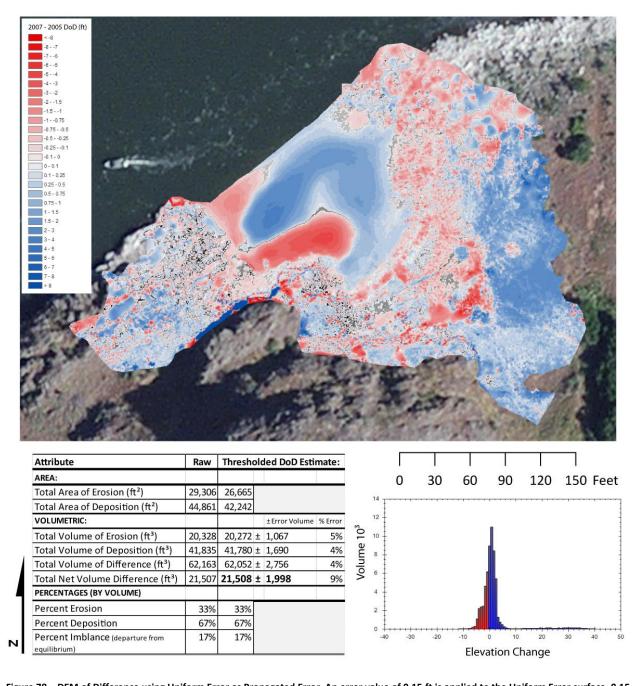


Figure 78 – DEM of Difference using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

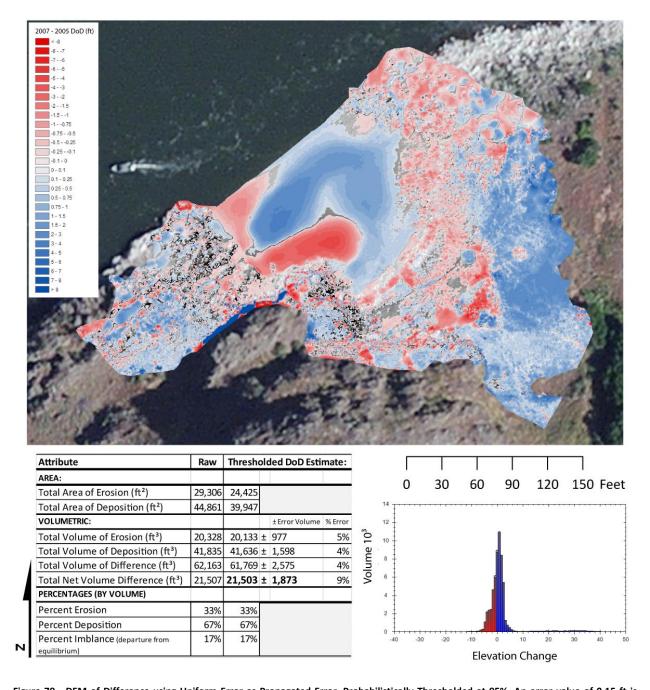
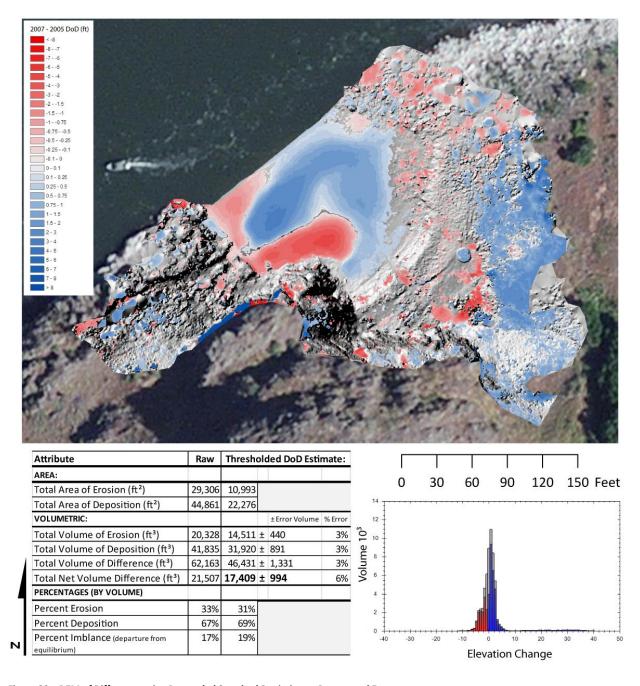


Figure 79 - DEM of Difference using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.



 $\label{eq:Figure 80-DEM of Difference using Detrended Standard Deviation as Propagated Error.$

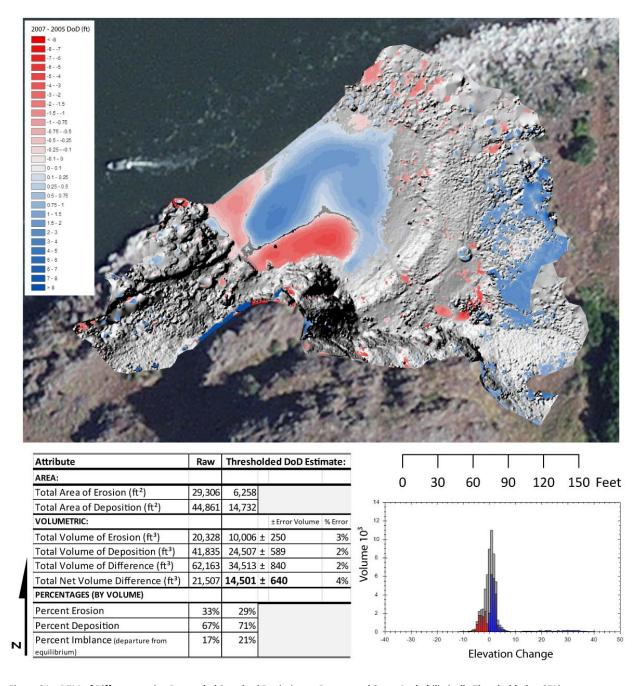


Figure 81 – DEM of Difference using Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%.

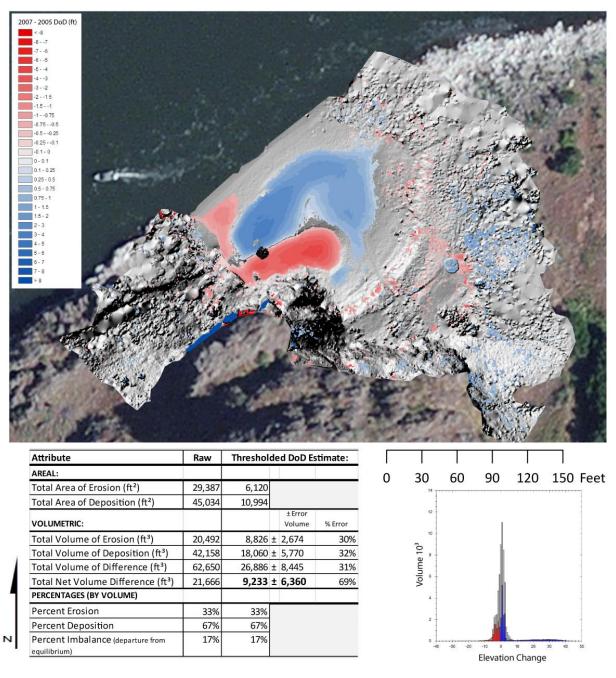


Figure 82 – DEM of Difference using the Fuzzy Inference System as Propagated Error. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

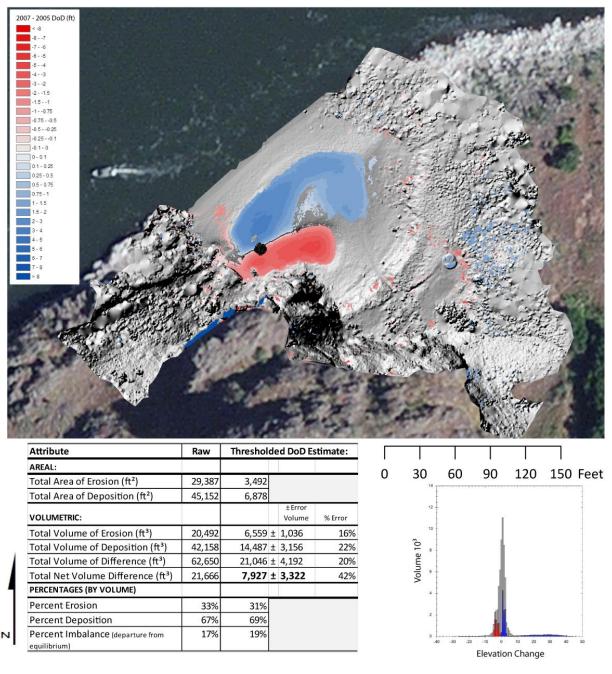


Figure 83 – DEM of Difference using the Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

2007-2006 DOD ANALYSIS

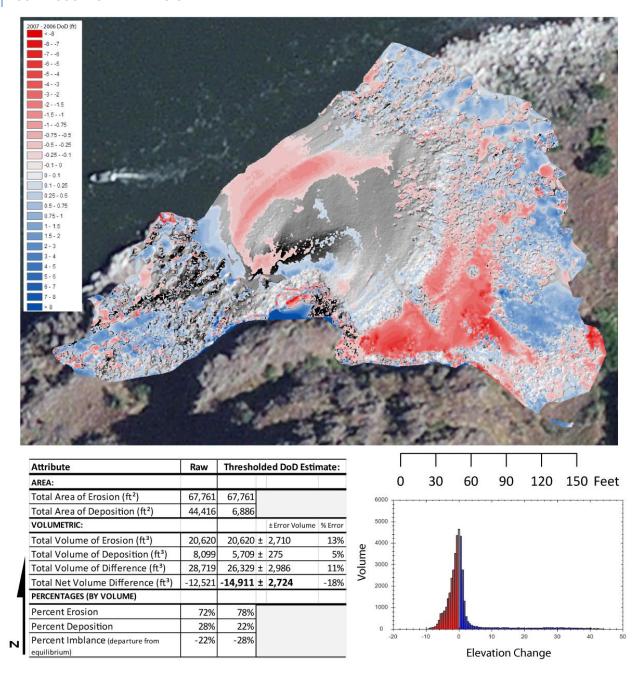


Figure 84 – DEM of Difference using Simple Minimum Level of Detection Thresholded at 0.15 ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

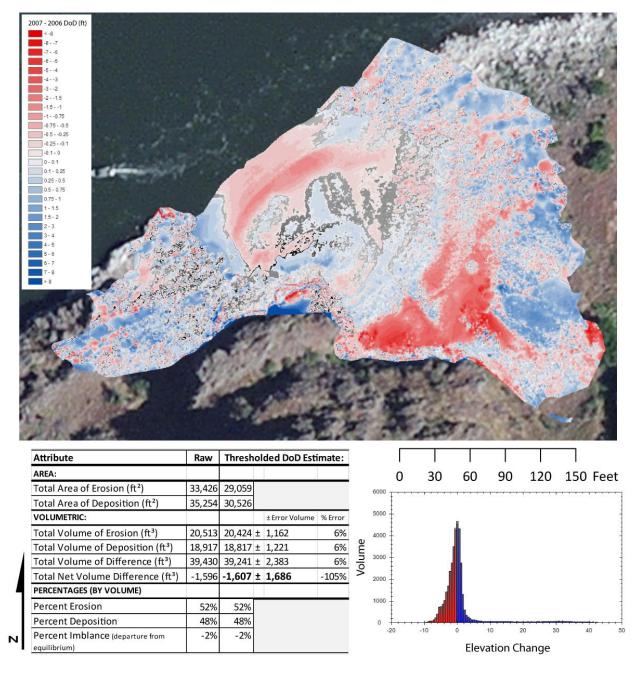


Figure 85 – DEM of Difference using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

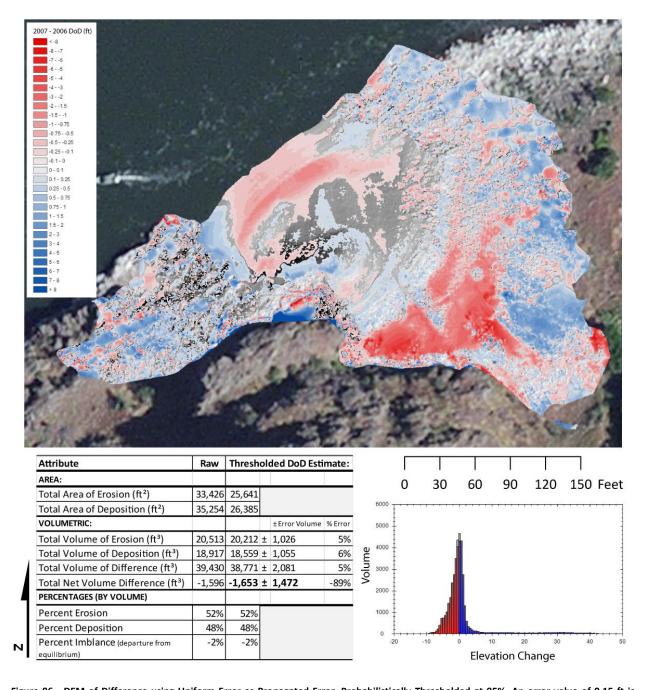


Figure 86 - DEM of Difference using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

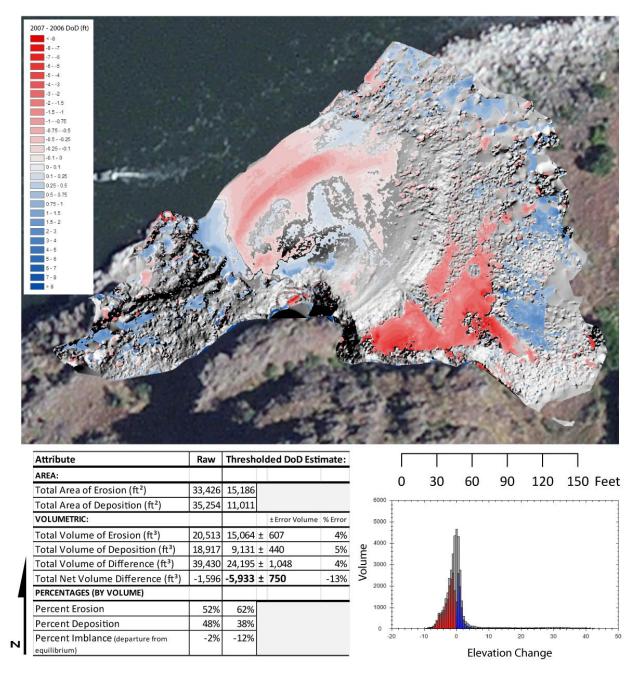


Figure 87 – DEM of Difference using Detrended Standard Deviation as Propagated Error.

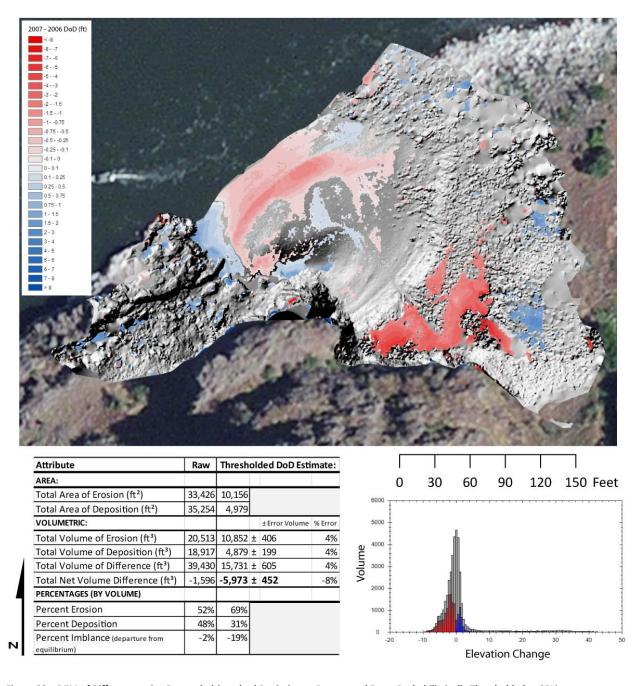


Figure 88 – DEM of Difference using Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%.

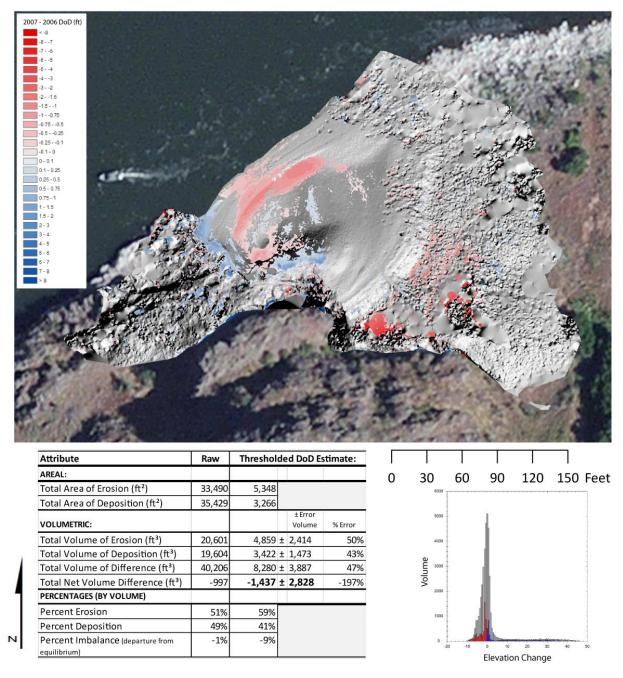


Figure 89 – DEM of Difference using the Fuzzy Inference System as Propagated Error. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

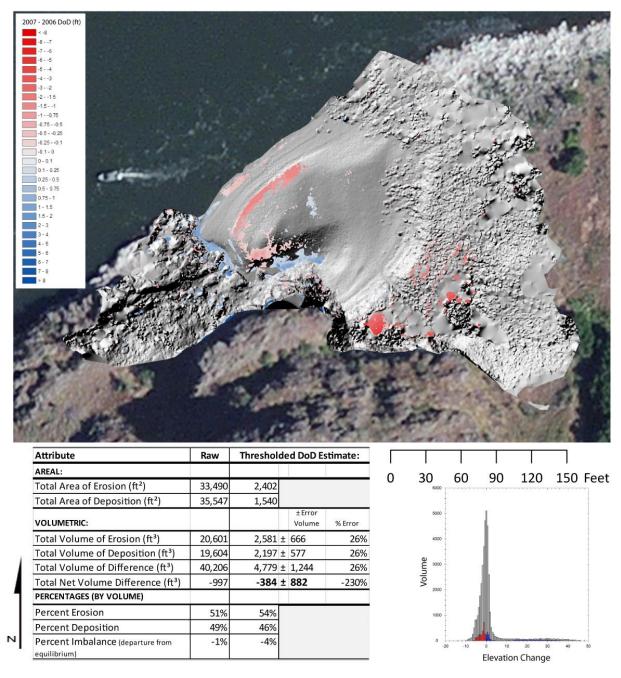


Figure 90 – DEM of Difference using the Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

2005 THROUGH 2007 TRANSIENT STORAGE ANALYSIS Max - Min DoD (ft) 0 - 0.1 0.1 - 0.25 0.25 - 0.5 0.5 - 0.75 0.75 - 11 - 1.5 1.5 - 2 4-5 5-6 Thresholded DoD Estimate: Attribute Raw AREA: 0 30 90 120 150 Feet 60 Total Area of Erosion (ft2) Total Area of Deposition (ft2) 173,940 80,461 VOLUMETRIC: ± Error Volume % Error Total Volume of Erosion (ft³) 0 ± 0 68,245 ± 3,218 Total Volume of Deposition (ft³) 74,825 5% Total Volume of Difference (ft3) 74,825 5% 68,245 ± 3,218 Total Net Volume Difference (ft³) 74,825 68,245 ± 3,218 5% PERCENTAGES (BY VOLUME) Percent Erosion 0% 0% Percent Deposition 100% 100% Percent Imblance (departure from 50% 50% equilibrium) **Elevation Change**

Figure 91 – Transient Storage using Simple Minimum Level of Detection Thresholded at 0.15 ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

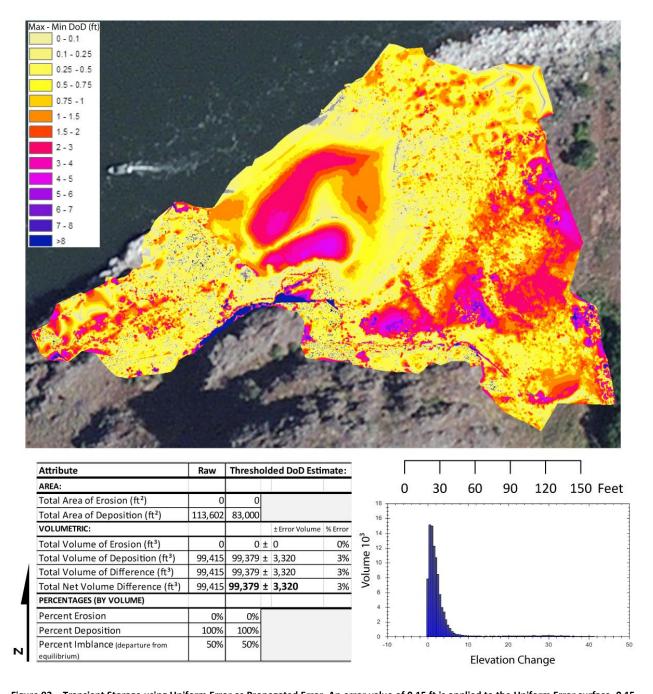


Figure 92 – Transient Storage using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

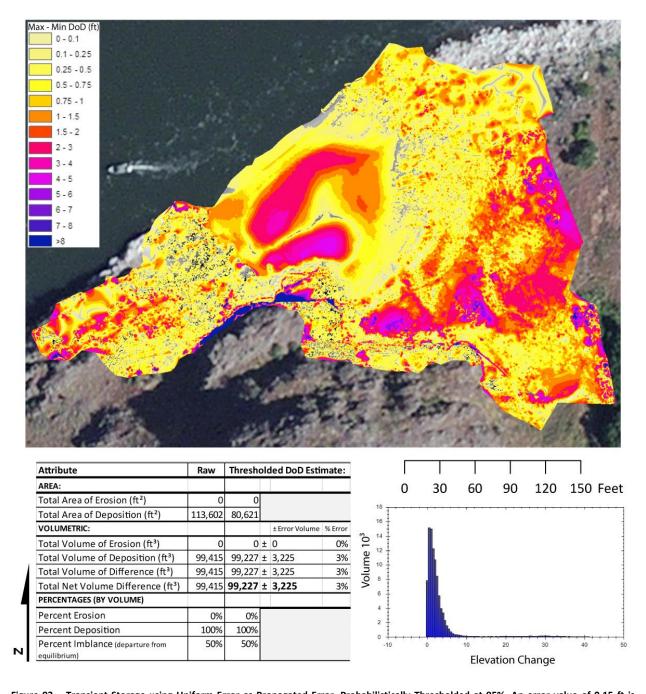


Figure 93 – Transient Storage using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

2006-2005 DOD ANALYSIS

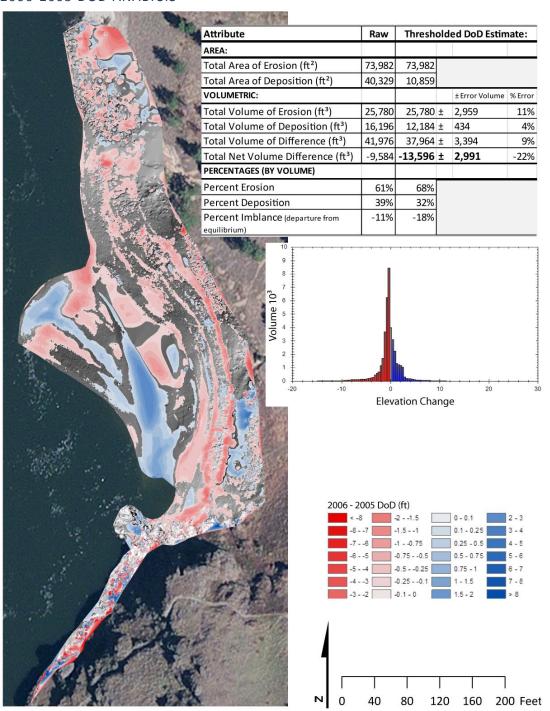


Figure 94 – DEM of Difference using Simple Minimum Level of Detection Threshold at 0.15ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

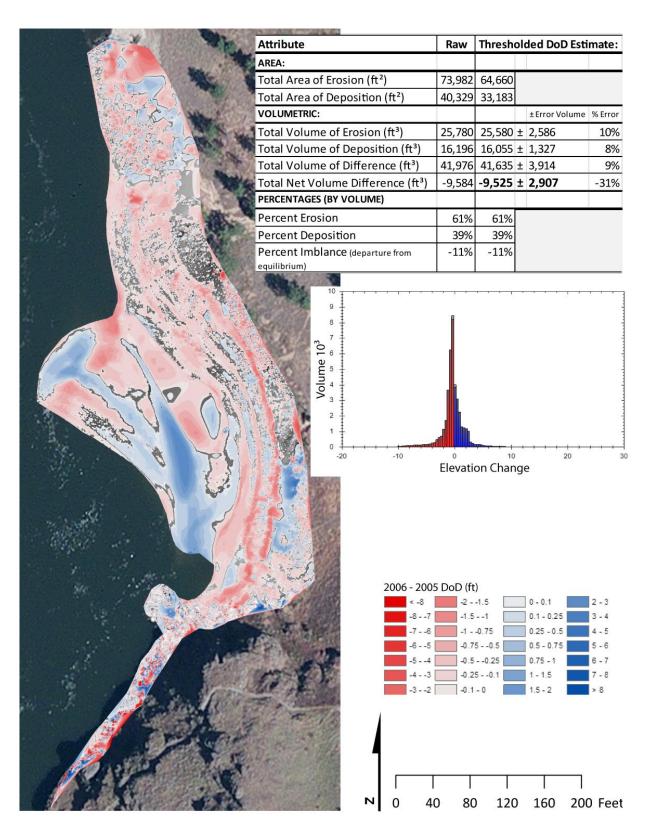


Figure 95 – DEM of Difference using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

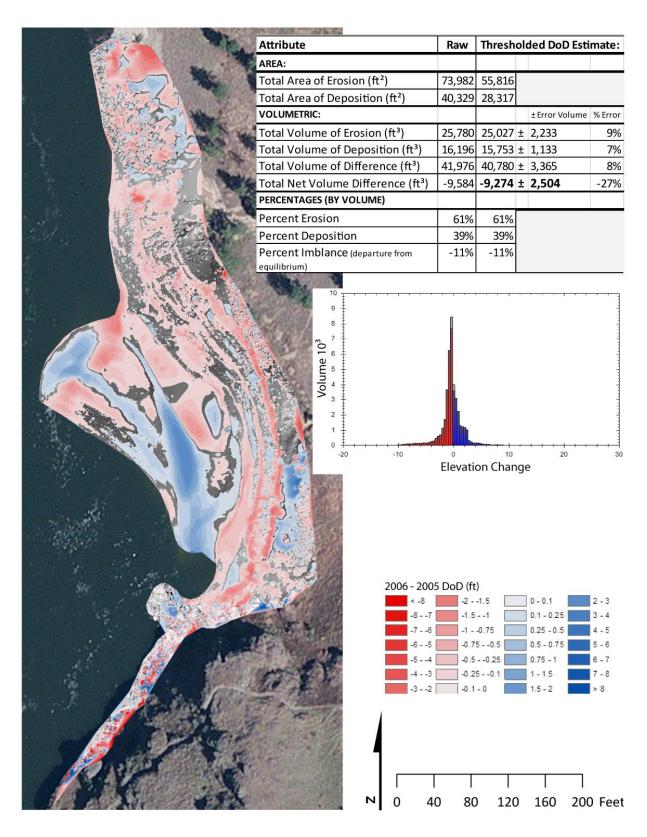


Figure 96 – DEM of Difference using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

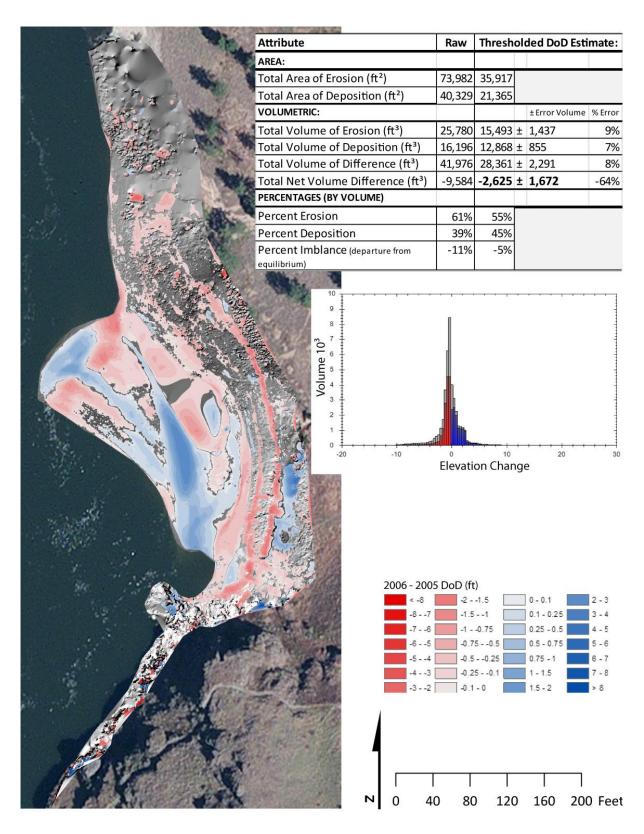


Figure 97 - DEM of Difference using Detrended Standard Deviation as Propagated Error.

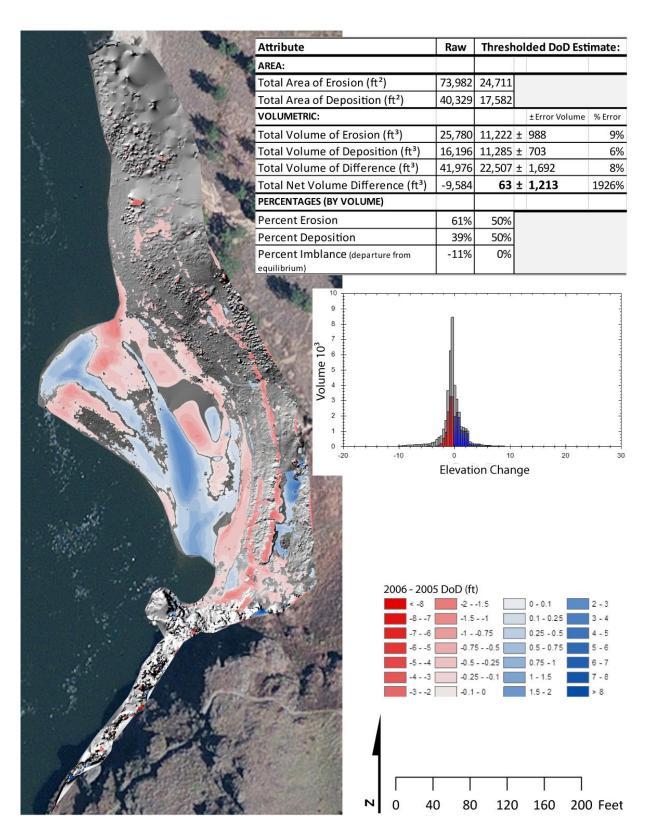


Figure 98 – DEM of Difference using Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%.

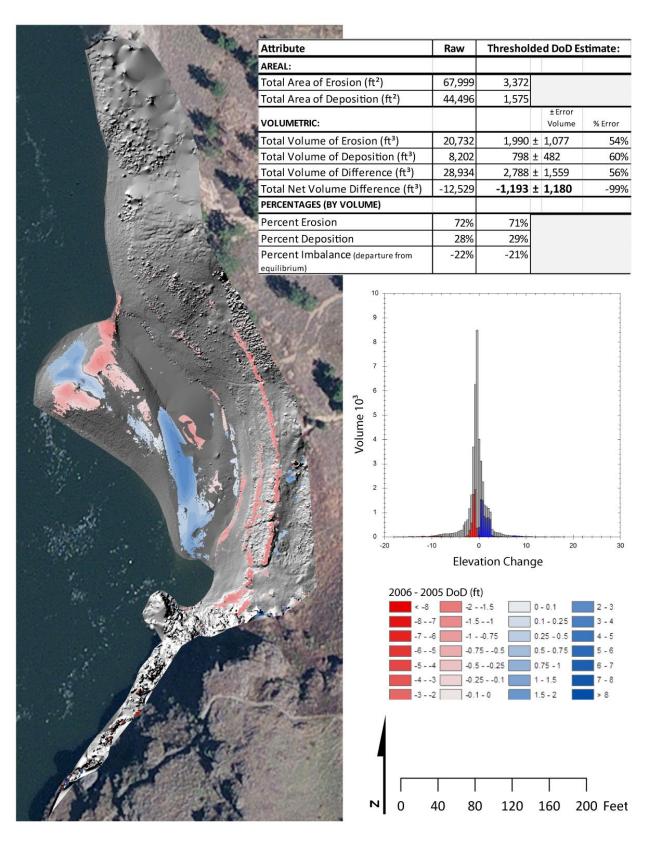


Figure 99 – DEM of Difference using the Fuzzy Inference System as Propagated Error. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

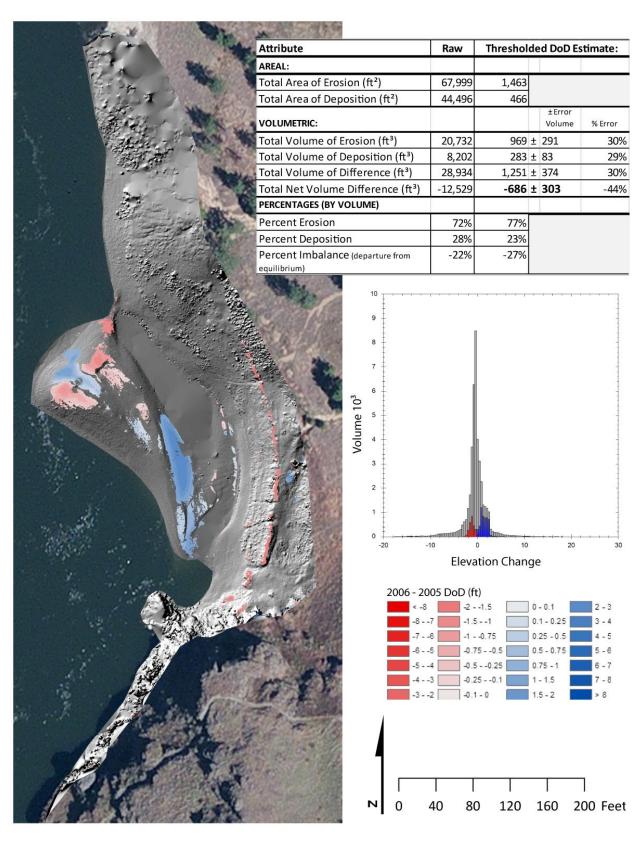


Figure 100 – DEM of Difference using the Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

2007-2005 DOD ANALYSIS

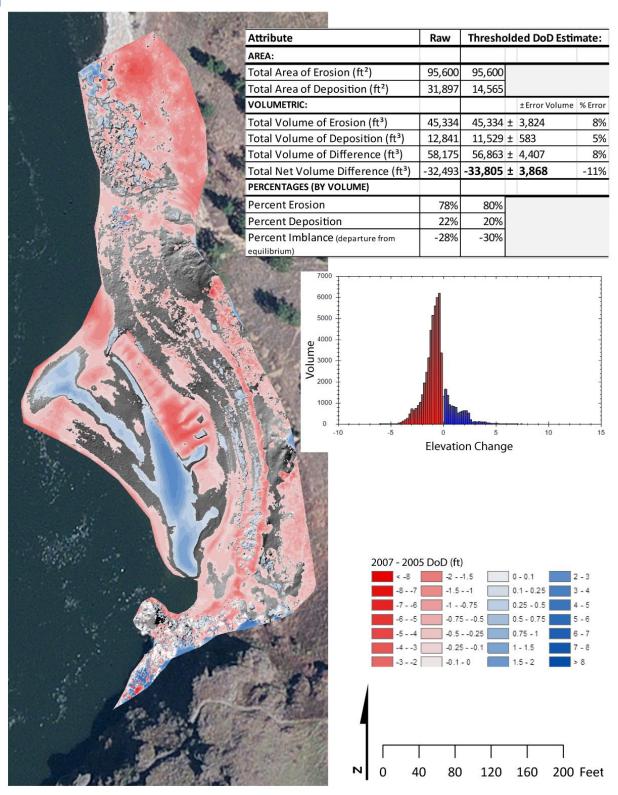


Figure 101 – DEM of Difference using Simple Minimum Level of Detection Threshold at 0.15ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

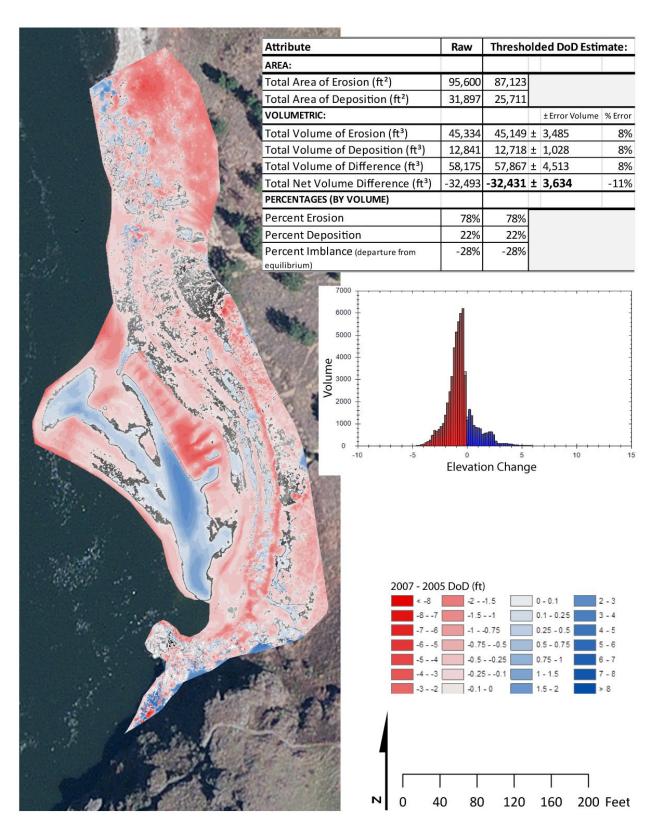


Figure 102 – DEM of Difference using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

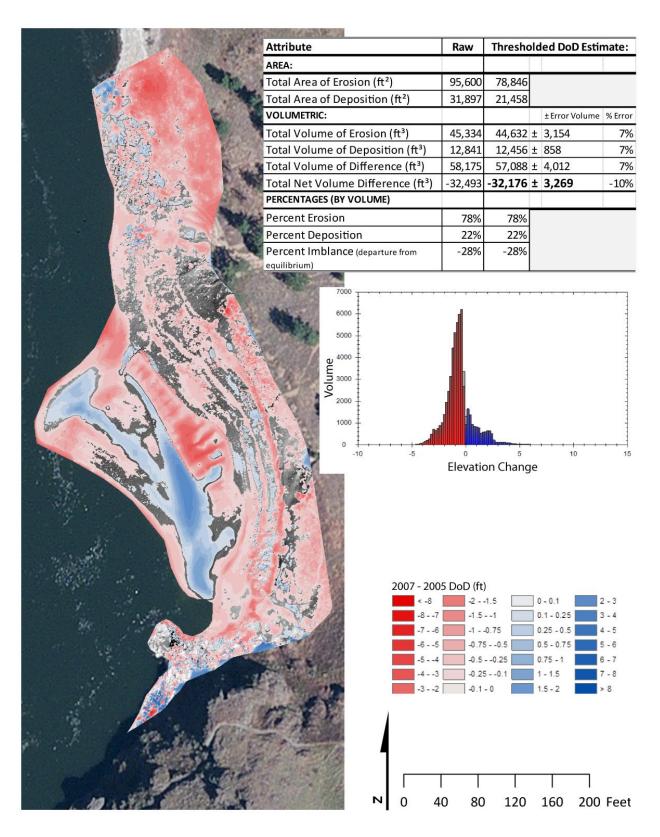


Figure 103 – DEM of Difference using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

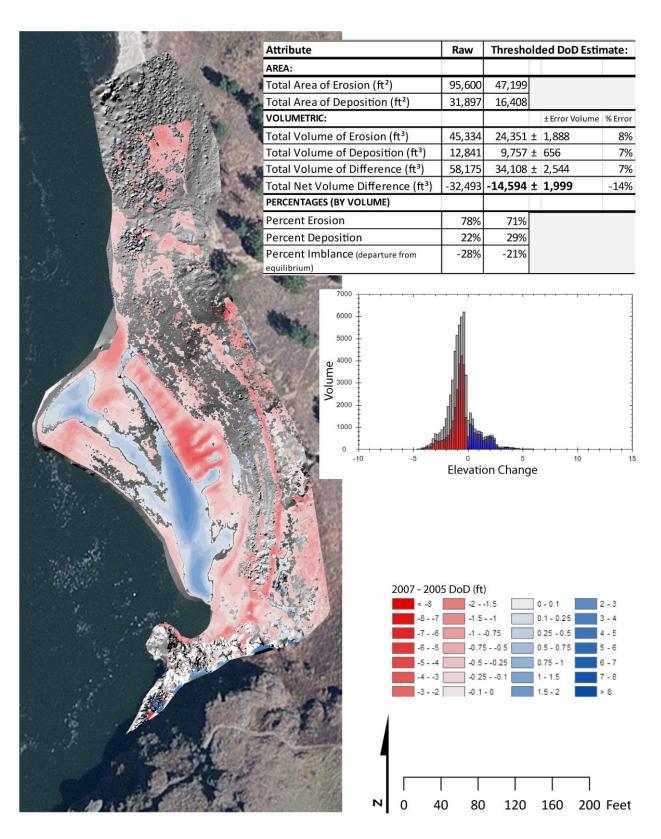


Figure 104 – DEM of Difference using Detrended Standard Deviation as Propagated Error.

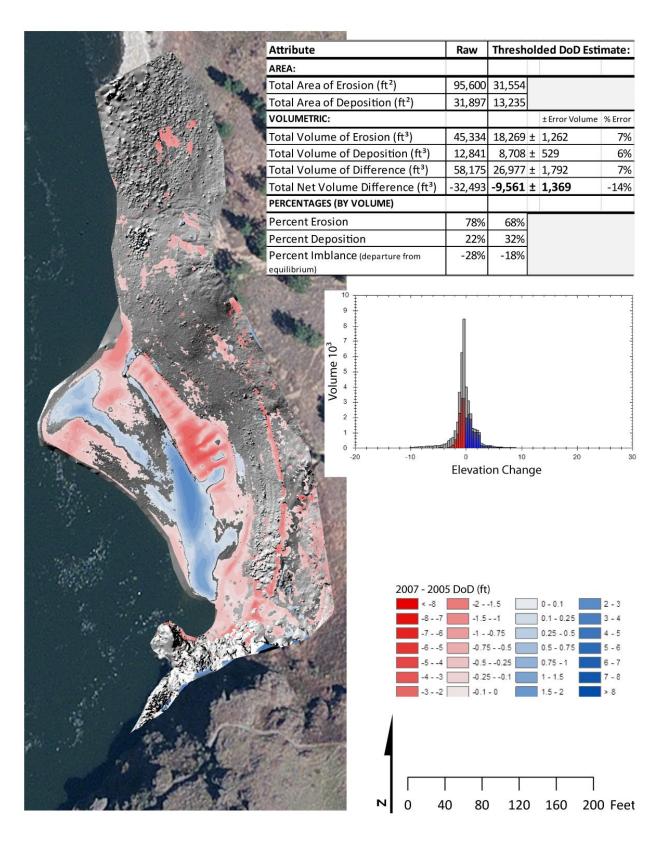


Figure 105 – DEM of Difference using Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%.

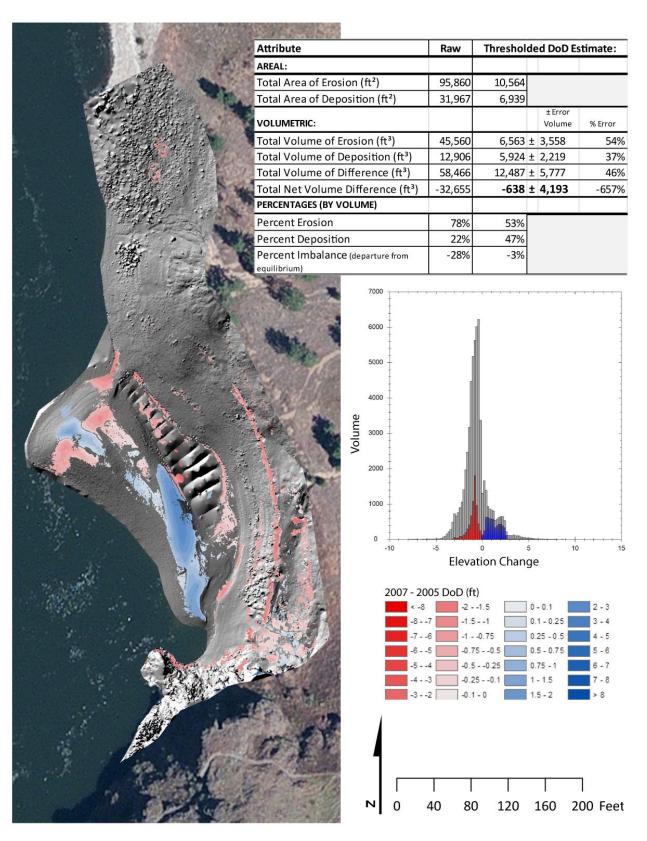


Figure 106 – DEM of Difference using the Fuzzy Inference System as Propagated Error. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

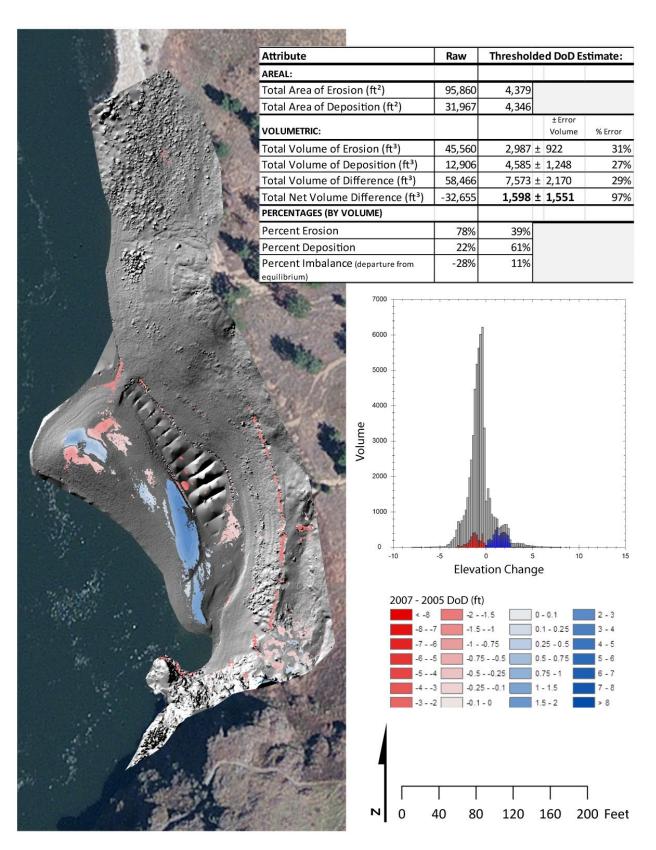


Figure 107 – DEM of Difference using the Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

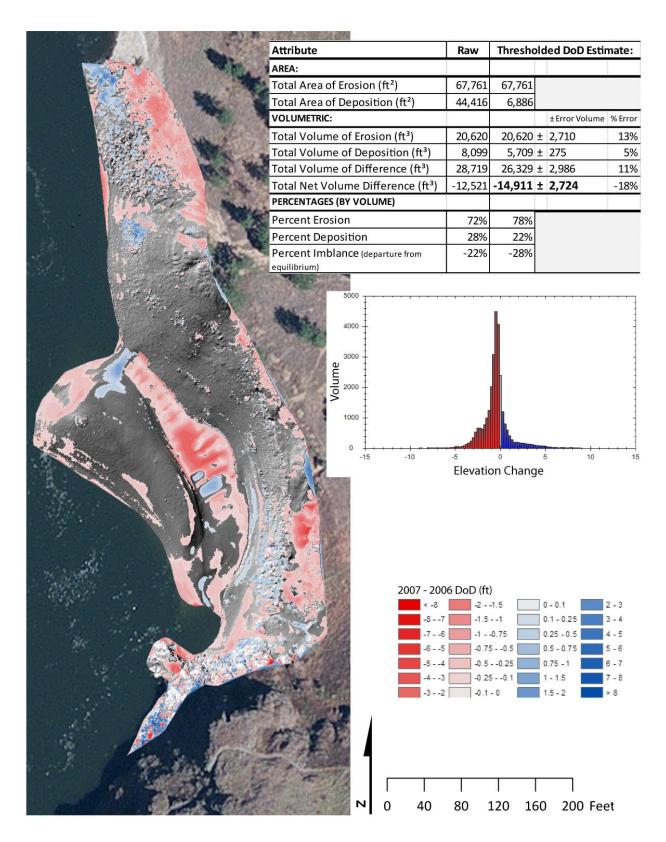


Figure 108 – DEM of Difference using Simple Minimum Level of Detection Threshold at 0.15ft. 0.15 ft is representative of the error associated with the equipment used during data collection.

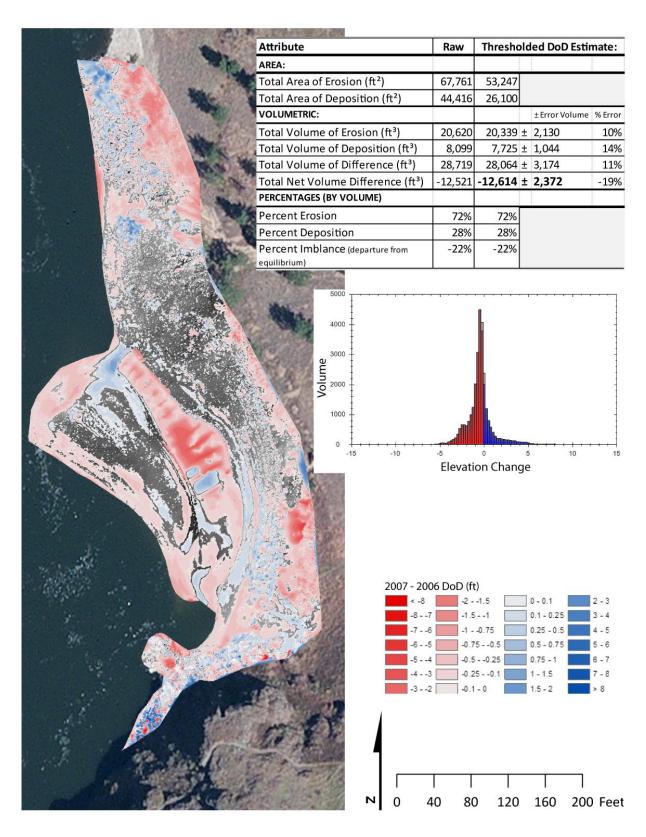


Figure 109 - - DEM of Difference using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

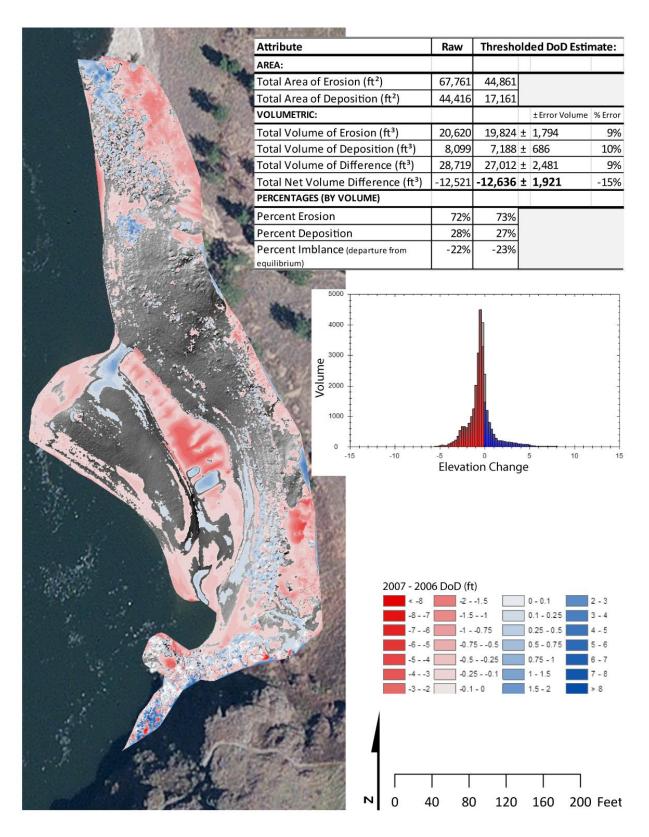


Figure 110 – DEM of Difference using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

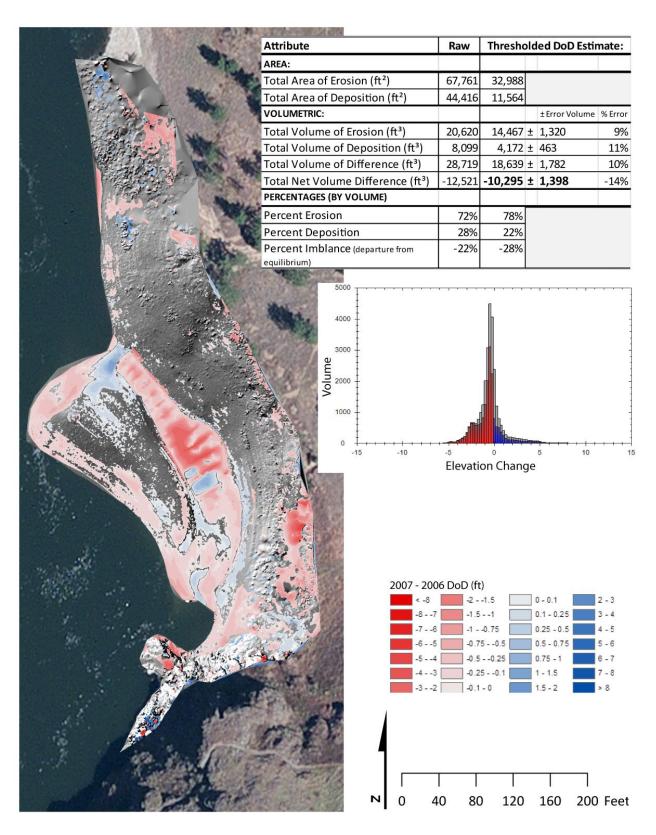


Figure 111 – DEM of Difference using Detrended Standard Deviation as Propagated Error.

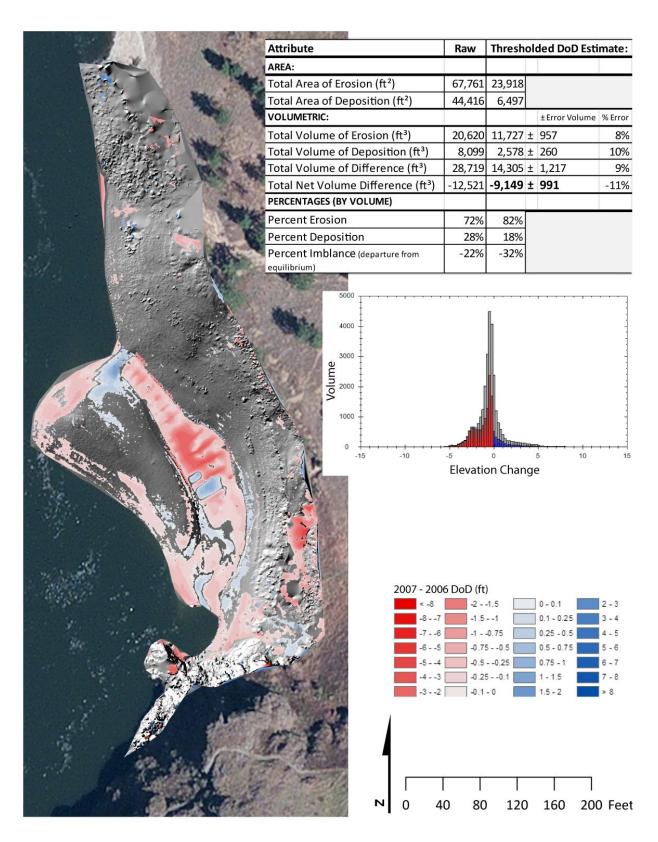


Figure 112 – DEM of Difference using Detrended Standard Deviation as Propagated Error, Probabilistically Thresholded at 95%.

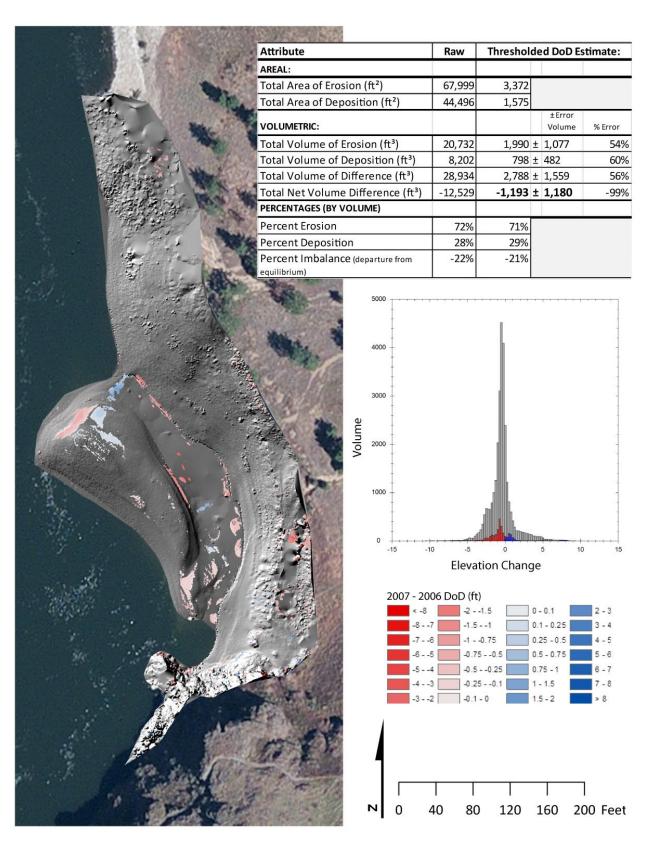


Figure 113 – DEM of Difference using the Fuzzy Inference System as Propagated Error. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

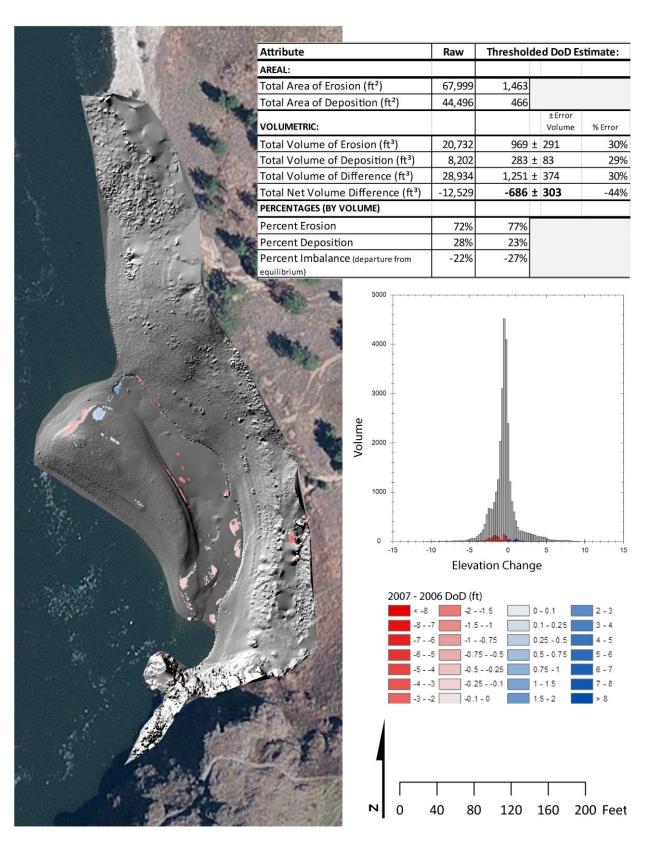


Figure 114 – DEM of Difference using the Fuzzy Inference System as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the FIS error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

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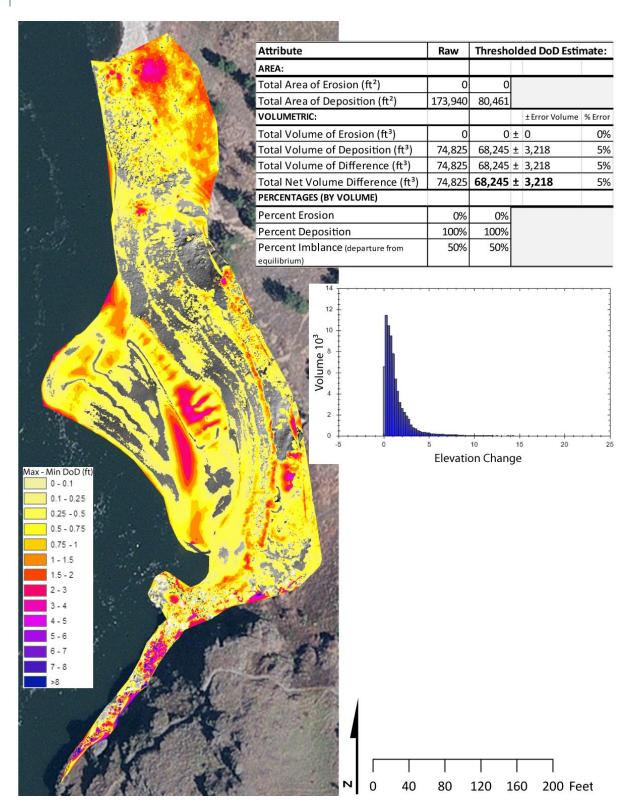


Figure 115 – Transient Storage using Simple Minimum Level of Detection Thresholded at 0.15 ft. 0.15 ft is representative of the error associated with the equipment used during data collection

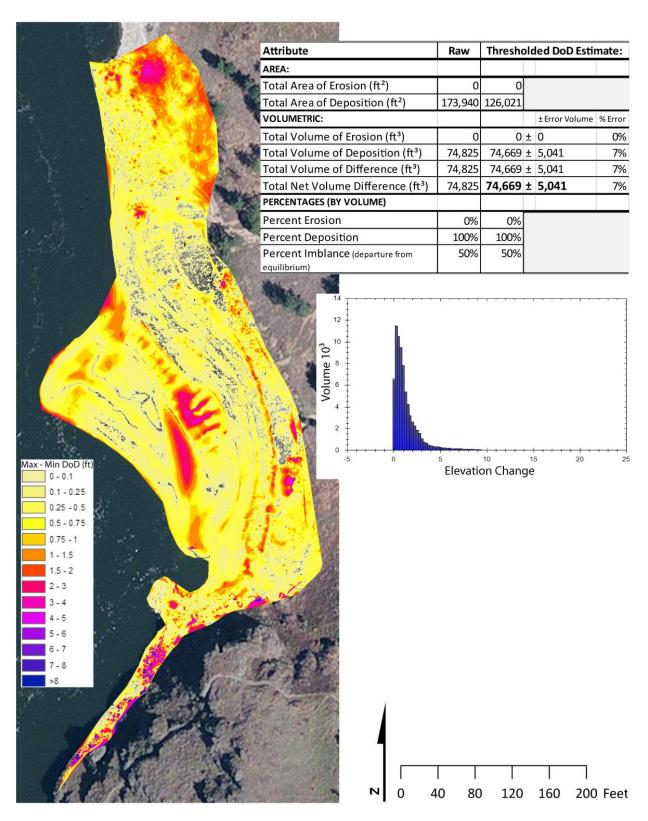


Figure 116 – Transient Storage using Uniform Error as Propagated Error. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.

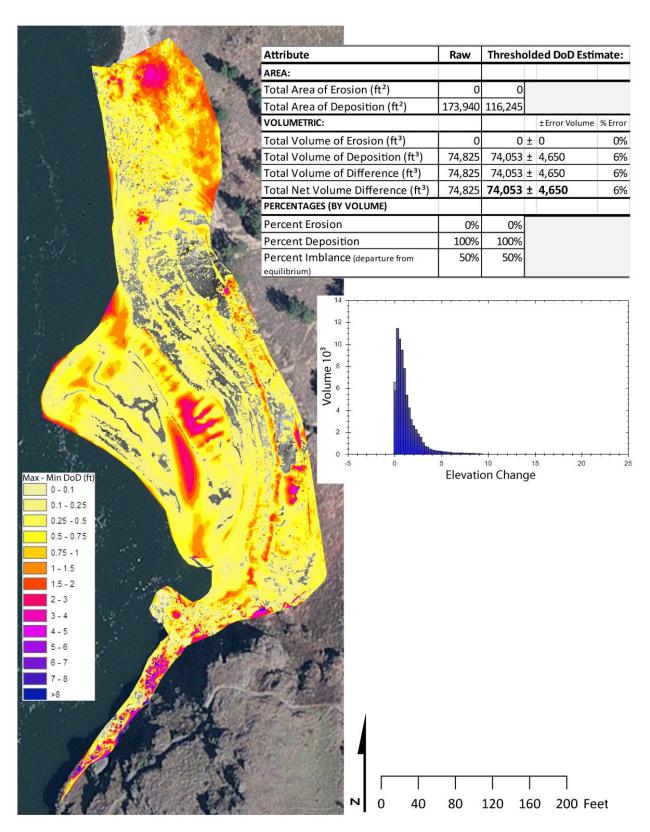


Figure 117 – Transient Storage using Uniform Error as Propagated Error, Probabilistically Thresholded at 95%. An error value of 0.15 ft is applied to the Uniform Error surface. 0.15 ft is representative of the error associated with the equipment used during data collection.