U.S. DEPARTMENT OF ENERGY

PNNL-19878

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Development of a High-Resolution Bathymetry Dataset for the Columbia River through the Hanford Reach

AM Coleman KB Larson
DL Ward JW Lettrick

September 2010

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Development of a High-Resolution Bathymetry Dataset for the Columbia River through the Hanford Reach

FINAL REPORT

AM Coleman KB Larson
DL Ward JW Lettrick

September 2010

Prepared for:

CH2MHILL Plateau Remediation Company
Richland, Washington
Under a Government Order with the U.S. Department of Energy
Contract DE-AC05-76RLO 1830

Prepared by:
Pacific Northwest National Laboratory
Richland, Washington

Executive Summary

A bathymetric and topographic data collection and processing effort involving existing and newly collected data has been performed for the Columbia River through the Hanford Reach in central Washington State, extending 60-miles from the tailrace of Priest Rapids Dam (river mile 397) to near the vicinity of the Interstate 182 bridge just upstream of the Yakima River confluence (river mile 337).

The contents of this report provide a description of the data collections, data inputs, processing methodology, and final data quality assessment used to develop a comprehensive and continuous merged bathymetric and topographic surface dataset for the Columbia River through the Hanford Reach. This work is a continuation of FY2009 work that focused on retrieving, assembling, and processing existing bathymetry and terrestrial topographic data (Coleman, 2009). At the conclusion of the FY2009 work, it was determined and recommended that additional data be collected to supplement existing bathymetric and topographic data to fill significant data gaps in the central portion of the Hanford Reach. In FY2010, hydrographic surveys were conducted and resulting data were cleaned, processed, quality checked against other sources, and incorporated into a multi-source data fusion process to produce a single high-resolution dataset to support the various DOE Hanford missions.

Acknowledgments

We appreciate the contributions to this study from the following PNNL staff:

- Travis Yeik
- Vibhav Durgesh
- Erin Hamilton

We acknowledge John Skalicky of the U.S. Fish and Wildlife Service, for without his support in providing key existing data products, this effort could not have progressed to the level it did.

We express our sincere appreciation to Dr. Scott Petersen at CHPRC for funding this fundamental data development effort and realizing the many values this data will have in the near and long-term for multi-disciplinary research and river protection throughout the Hanford Reach.

Contents

Figures

1.0 Introduction

This report provides a description of the data collection, data inputs, processing methodology, and final data quality assessment used to develop a comprehensive and continuous merged bathymetric and topographic surface dataset for the Columbia River through the Hanford Reach, a 60-mile stretch of unimpounded river located in south central Washington State. This work is a continuation of FY2009 work that focused on retrieving, assembling, and processing existing bathymetry and terrestrial topographic data (Coleman, 2009). At the conclusion of the FY2009 work, it was determined and recommended that additional data be collected to supplement existing bathymetric and topographic data to fill significant data gaps in the central portion of the Hanford Reach. In FY2010, hydrographic surveys were conducted and resulting data were cleaned, processed, quality checked against other sources, and incorporated into a multi-source data fusion process to produce a single high-resolution dataset to support the various DOE Hanford missions.

The contents of this report include a review of the existing data sources used, a description of the hydrographic surveys that were conducted, the data cleaning process, a review of the source and final data integrity, the processing methods used to assemble the final dataset, and finally, the mechanism developed for disseminating the data to users.

1.1 Background

The definition of the Hanford Reach in this report refers to the Columbia River and its immediate environs from the tailrace of Priest Rapids Dam (river mile 397) to near the vicinity of the Interstate 182 bridge just upstream of the Yakima River confluence (river mile 337) in central Washington State (see Figure 1). This section of river is 60 miles (97 kilometers) long, is adjacent to the Department of Energy's Hanford Site and is largely encompassed within the Hanford Reach National Monument managed by U.S. Fish and Wildlife Service (USFWS).

Prior to 2003, the only known efforts to develop a bathymetric data surface were within PNNL, primarily using a triangulated irregular network (TIN) based approach on U.S. Army Corps of Engineer (USACE) cross-section data, and where it existed, data from a 1998 SHOALS hydrographic LiDAR collection effort. These bathymetric surfaces were generated to support USDOE-funded hydrodynamic modeling efforts within the Hanford Reach. Through these and other bathymetric processing efforts, it was realized the TIN-based approach for bathymetric surfaces left too many artifacts and could be improved upon.

Starting in 2003, the U.S. Fish and Wildlife Service (USFWS) began collecting data to construct a high-resolution bathymetric surface for the Hanford Reach (Anglin et al., 2006). Upon review of the data, the terrain processing methods used were general purpose (also TIN-based) and tended to miss crucial terrain details that can be extracted from the source data, particularly the high-density hydrographic Light Detection and Ranging (LiDAR) sourced data. In addition, it was reported that some of the hydrographic survey data used in the development of the bathymetric surface, particularly from the 1990's BPA-funded White Sturgeon project (Anglin 1996, Angin et al. 1997, Anglin et al. 1998) are considered inaccurate partly due to the use of an Acoustic Doppler Current Profiler (ADCP) to collect bottom elevations. Since the 2006 USFWS effort, new terrestrial LiDAR data have been collected for the USDOE Hanford Site and provides an excellent and high-resolution, high-accuracy product to merge with

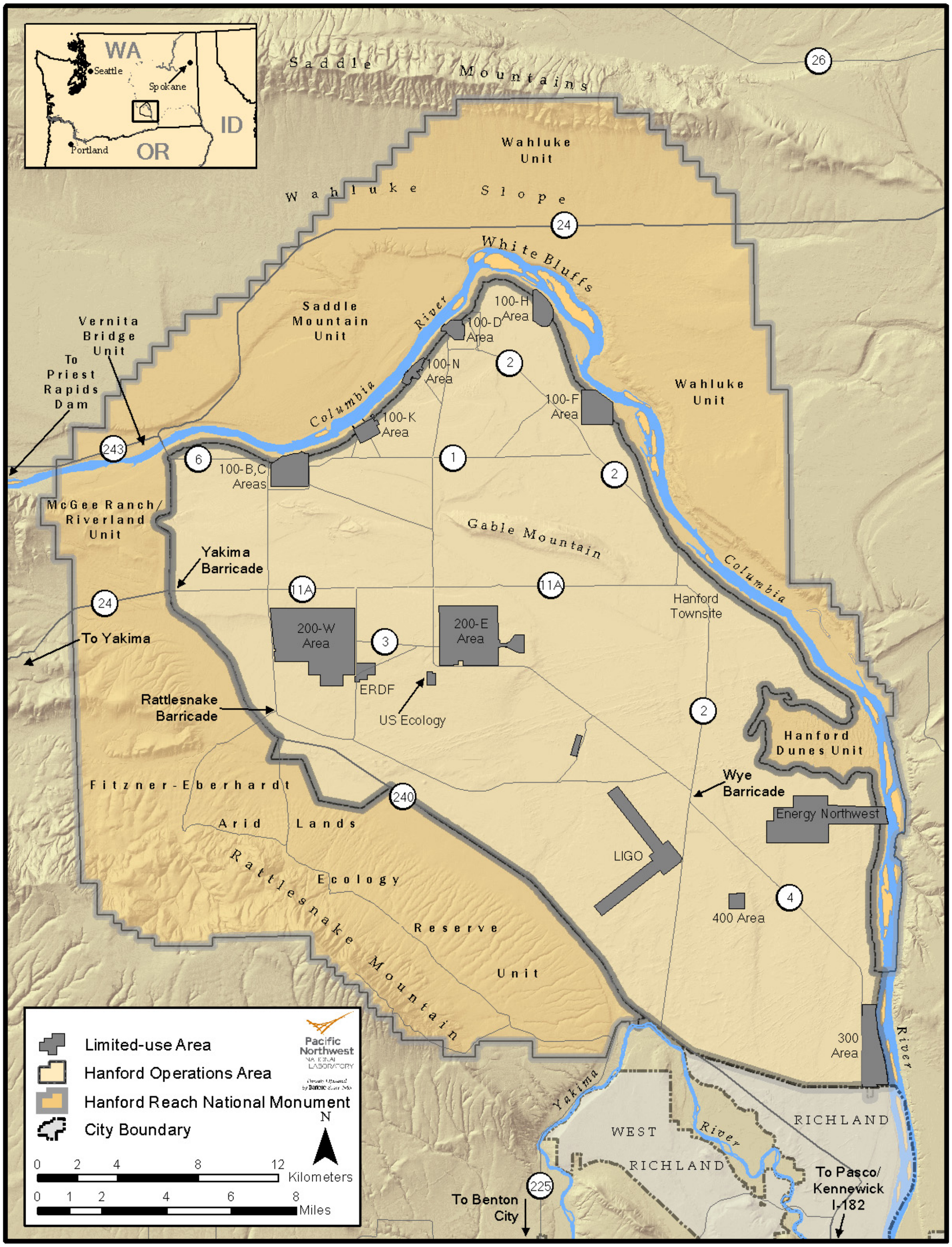

Figure 1. The Columbia River through the Hanford Reach National Monument and adjacent U.S. Department of Energy's Hanford Site in south-central Washington State.

other prior collected bathymetric data. The high-resolution topographic data provides an important element for groundwater/river interface studies in a hydrosystem-influenced environment that experiences daily fluctuating water surface elevations. Note that the newly collected topographic LiDAR does not cover the entire extent of the study area, only the areas within and immediately adjacent to the USDOE Hanford Site. The data collection efforts under the 2006 USFWS project provided key raw data products to build an updated bathymetric surface.

The specific objective of this project was to pull the most current, best quality data for the Hanford Reach and compile a 1-meter resolution merged bathymetric/topographic surface using state-of-the-art terrain processing and analysis methods and formulate a high-quality terrain surface for the Hanford Reach. The final data product of this work can be used for numerous studies from groundwater/surface water interactions, contaminant fate and transport, monitoring, salmon stranding, specie pattern analysis, hydrodynamic modeling, groundwater modeling, and risk management, all of which support the overall DOE mission at Hanford. In FY2009, the processing of 41-miles of bathymetry data was completed and it was determined that additional data collections over a 19-mile section would be required to fill in data gaps from a 1998 SHOALS LiDAR survey (see Figure 2). In FY2010, all data requirements were met and a merged topographic/bathymetric data product was generated. The methods and analysis are described herein.

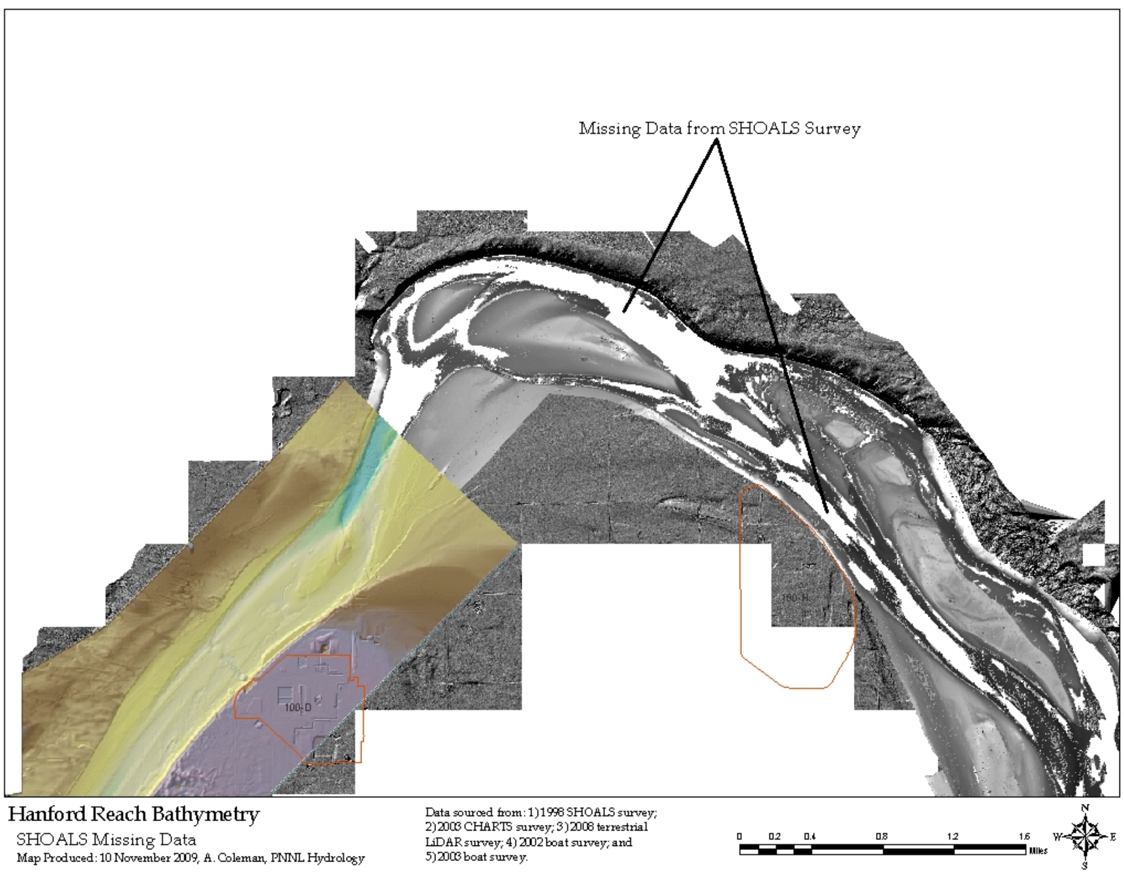

Figure 2. The1998 SHOALS data exhibits missing data in deep-water areas where the LiDAR signal was either absorbed in the water column and not returned to the sensor or returned erroneous data in very shallow water zones and areas with saturated soils.

2.0 Methodology

2.1 Data Sources

A total of six existing and one newly generated dataset were used to compile the bathymetric surface into its current state. Figure 3 provides a general overview of the extents of the primary datasets discussed below.

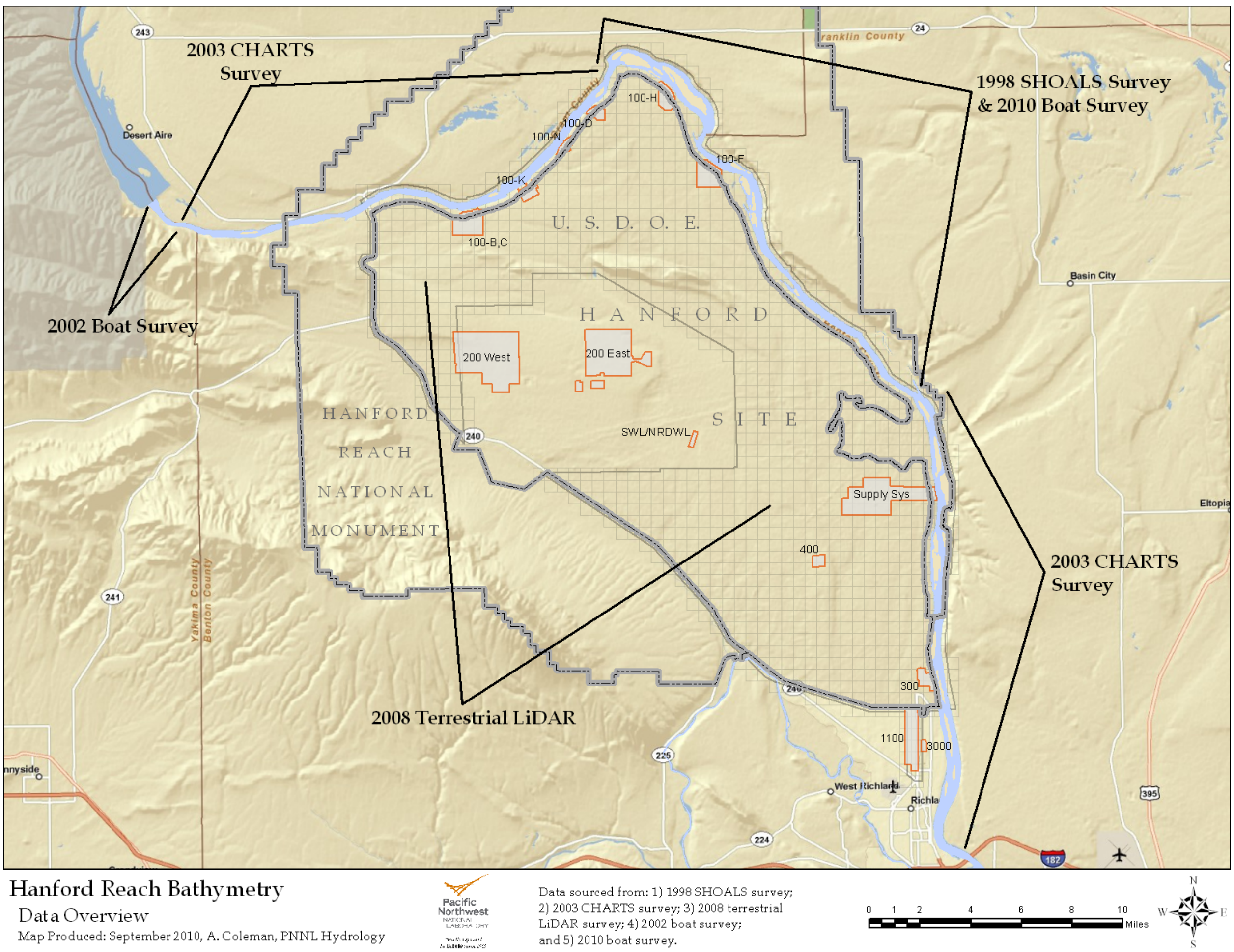

Figure 3. An overview of the primary topographic and bathymetric datasets used for assembling the Hanford Reach terrain model.

1) **Scanning Hydrographic Operational Airborne LiDAR Survey (SHOALS)**: The U.S. Army Corps of Engineers' Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) operates a special Light Detection and Ranging instrument that is capable of penetrating through water (up to 1.5x secchi disk depth) to collect both topographic and bathymetric elevation data. In 1998, the USGS Biological Resources Division's Columbia River Research Laboratory tasked the JALBTCX to collect data in the Hanford Reach from river miles 357-377 (Tiffan et al., 2002). The objective of this collection was to capture detailed data for determining salmon rearing habitat and provided a good dataset; however, deep-water areas were not captured due to lack of signal penetration through the water column (see Figure 4). PNNL was a direct recipient of this data.

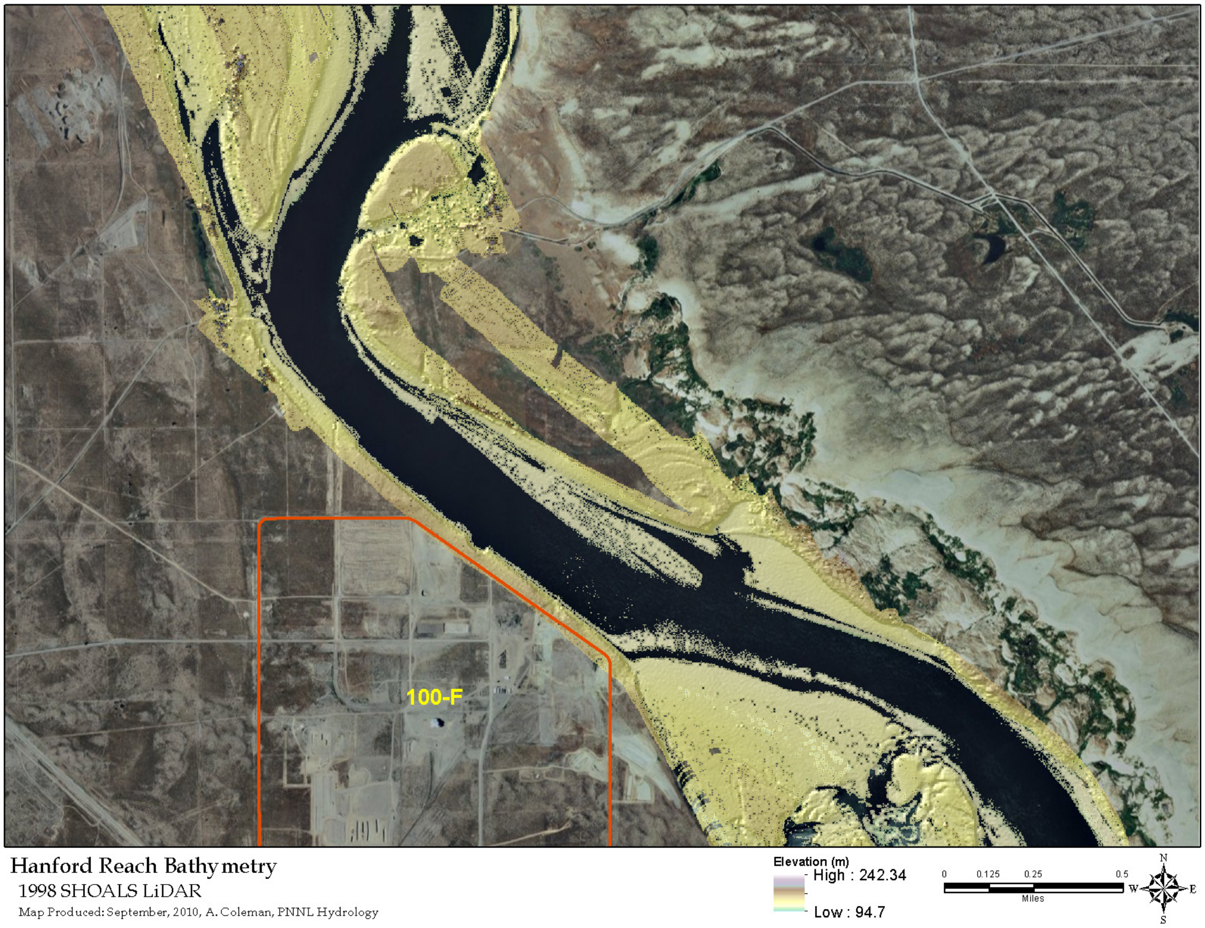

Figure 4. An example of the 1998 hydrographic SHOALS LiDAR data. Deep water areas and near-shore shallow areas are missing data.

2) **Compact Hydrographic Airborne Rapid Total Survey (CHARTS):** In October 2003, the U.S. Army Corps of Engineers' Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) was tasked by the USFWS to use a next-generation bathymetric LiDAR technology, referred to as CHARTS, to collect high-resolution bathymetric and topographic data for areas adjacent in extent to the original SHOALS data collection area. The areas of collection were segmented into an 'upper' and 'lower' section spanning river miles 377-395 and 337-357, respectively, within the Columbia River 400 kcfs boundary. The CHARTS system is a highly-specialized system which integrates a 1,000 Hz hydrographic LiDAR instrument, a 10,000 Hz topographic LiDAR, and a 1 Hz digital camera. The lower-frequency component of the CHARTS system is capable of penetrating water between 0.1 meters and 50-meters of depth (3x secchi disk depth) and the average horizontal spacing for hydro-based points is 2-5 meters where terrestrial points are spaced at 1-2 meters (see Figure 5). Figure 6 illustrates the CHARTS data extent and the high-resolution continuous coverage it offers. The multi-signal raw LiDAR data were released from USFWS to PNNL by special request in 2006.

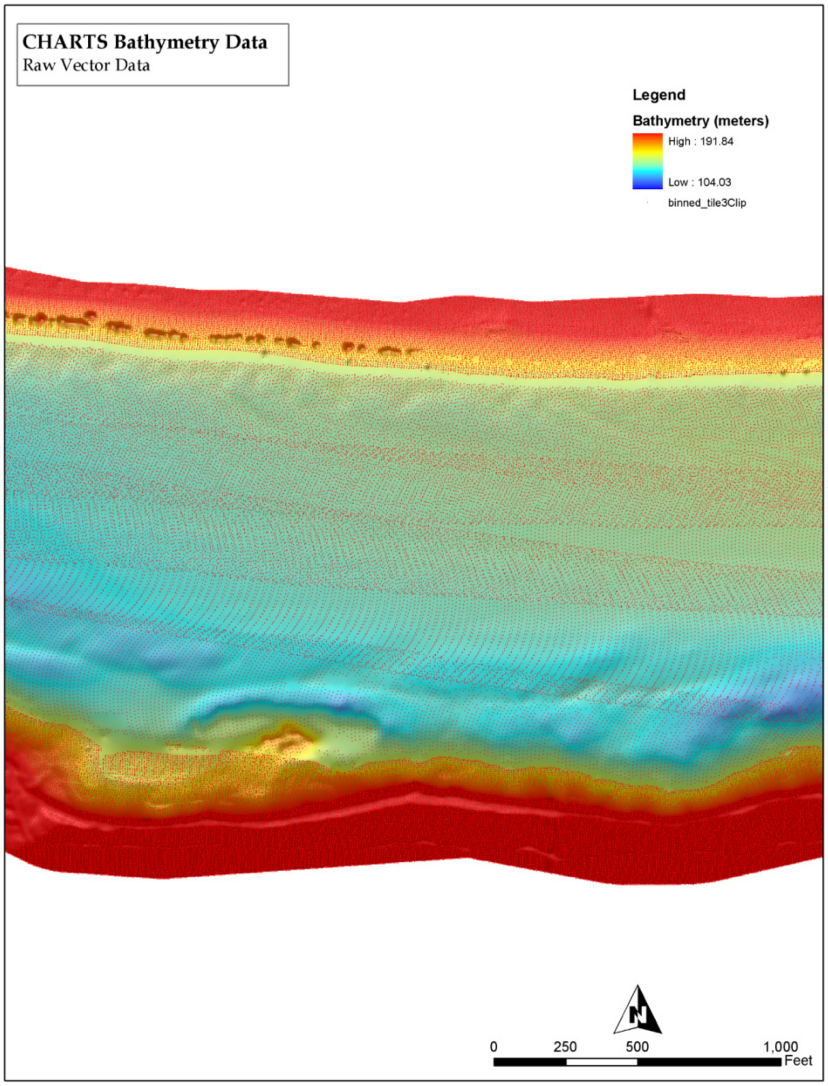

Figure 5. The red dots provide an example of the irregular spatial distributions of the CHARTS point data collections. The underlying hypsographic shaded terrain surface is the resulting product. Note the presence of riparian vegetation on the north bank that needed to be cleaned/filtered.

3) **Terrestrial/Topographic LiDAR for the Hanford Site:** A significant dataset to support the near-shore terrain construction comes from a 2008 LiDAR dataset collected by Aero-Metric of Seattle and tasked by Washington Closure Hanford. This critical piece of data allows for the culmination of bathymetric data and topographic data. This dataset covers a majority of the river corridor area extending from river miles 344-395. There are some areas where the terrain coverage on the river-left bank/Franklin County side is minimal (e.g., Savage Island). Discussions with Aero-Metric concluded there wasn't any additional data collected to fill these areas. The north and south extents of this data cover only to the official Hanford Site boundary, thus downstream of the 300-area, near-shore topography is missing.

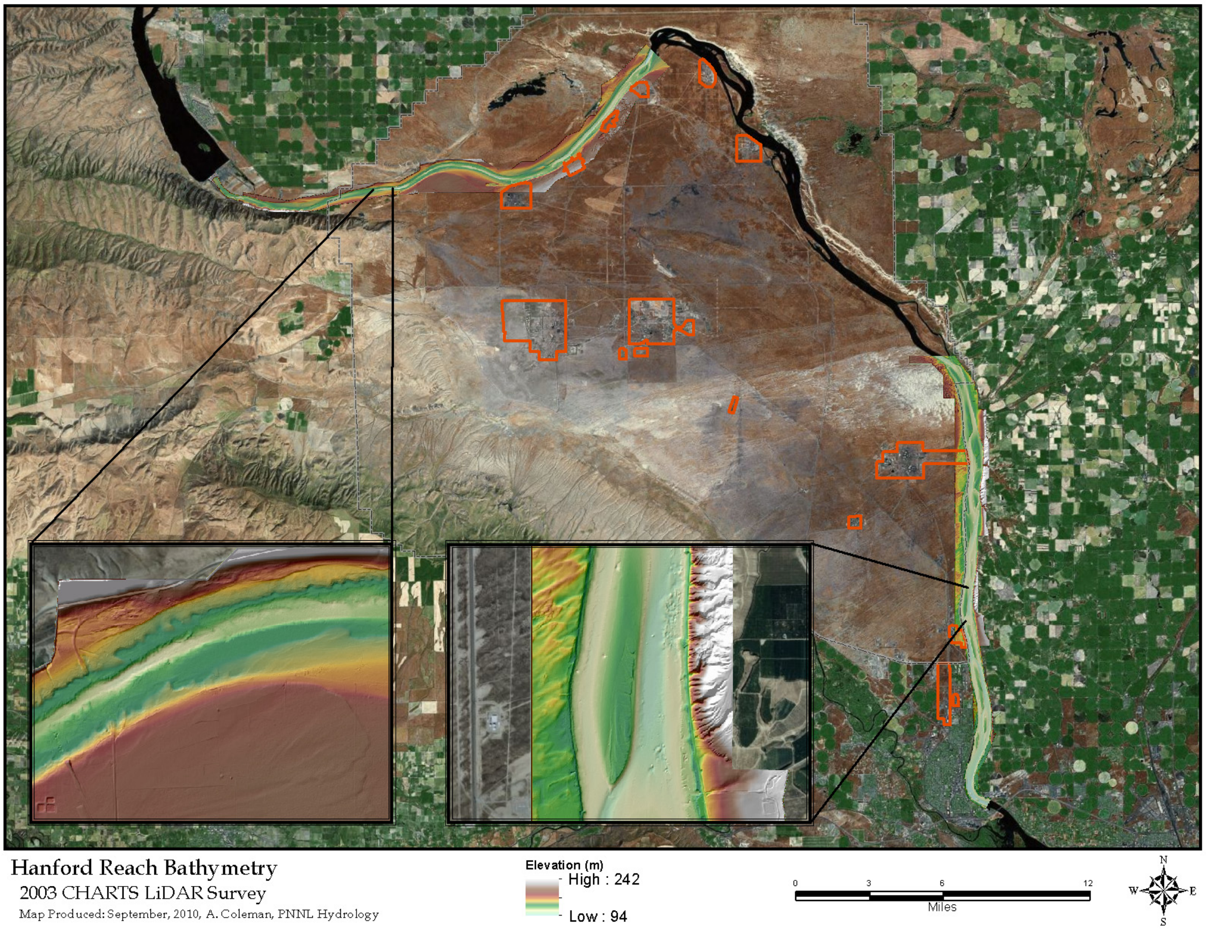

Figure 6. The 2003 CHARTS LiDAR 'upper' and 'lower' survey covered significant portions of the Hanford Reach excluding the middle zone where the 1998 CHARTS survey was conducted.

4) **Deep Water Bathymetric Boat Surveys for CHARTS:** To supplement very shallow water areas and deep water areas, the USFWS completed boat-based bathymetric surveys for select areas within the extents of the CHARTS data collection area with the specific purpose of capturing missing CHARTS data (Anglin et al., 2006). These surveys were conducted in December of 2003 and raw point data was provided to PNNL, by special request, in August 2009.

5) **Hydrographic Surveys of the Priest Rapids Tailrace:** In 2002, PNNL collected bathymetric survey data in the Priest Rapids Dam tailrace extending approximately from river miles 395-397. Because the CHARTS survey did not extend all the way to Priest Rapids Dam, this data was used as a supplement; however, this section of the river corridor only includes in-channel data and no near-shore terrestrial elevations.

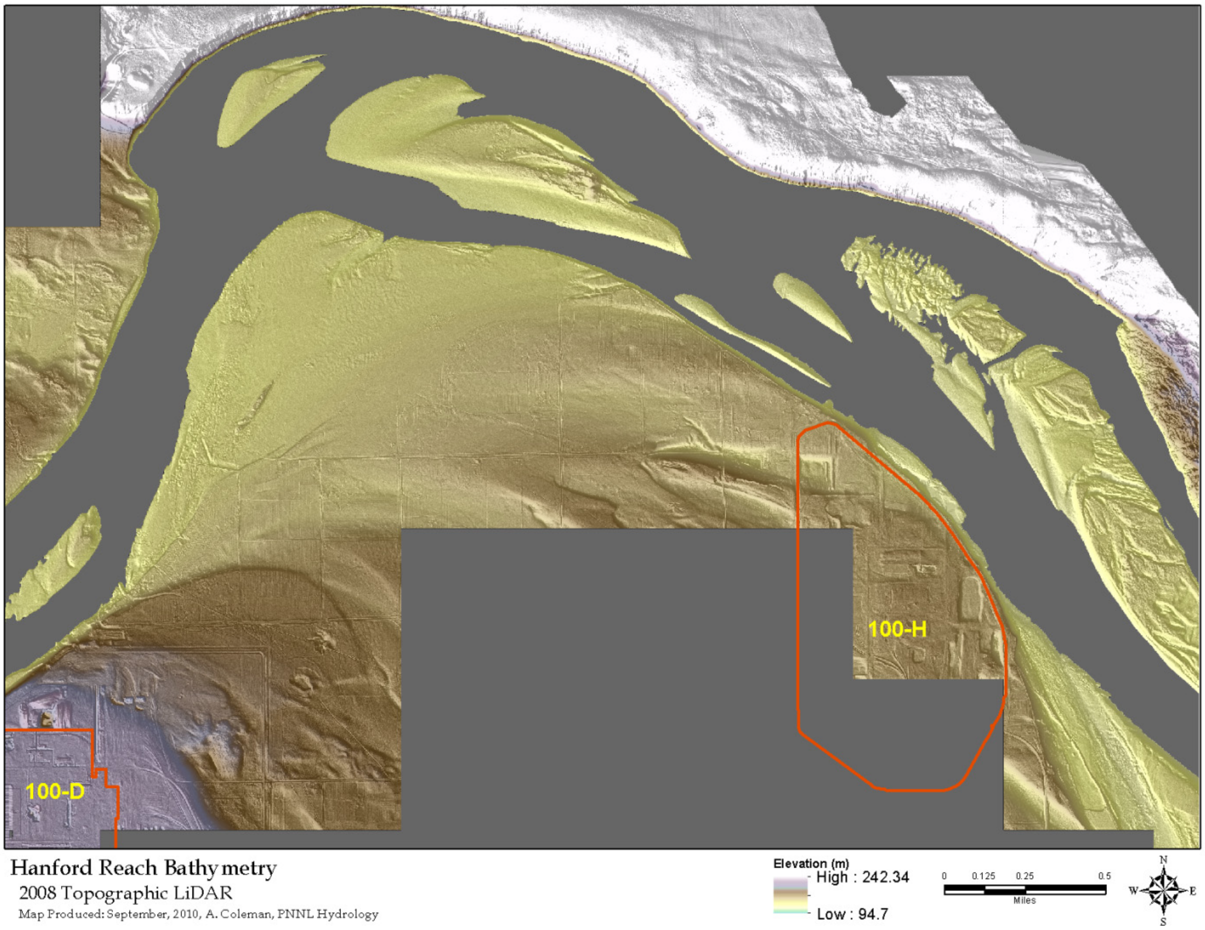

Figure 7. An example of the high-resolution topographic LiDAR data collected in 2008.

6) **Photogrammetrically Collected Elevations:** In the Fall of 2001, stereo aerial photographs were collected for a salmon redds survey and encompasses a 13-mile section of the Hanford Reach (similar area as SHOALS coverage). One of the data products of this effort was an aerotriangulated terrain model that was developed and used to orthorectify aerial imagery. In several cases, the 2008 Terrestrial LiDAR data set had data gaps in between tiles, for which these 2001 collected data were used to fill the gaps.

7) **2010 Hydrographic Surveys of the SHOALS Zone:** In response to recommendations made by Coleman (2009), a hydrographic survey was performed to fill in missing data not covered by the 1998 SHOALS LiDAR survey; these primarily included deep water and very shallow water areas (see Figure 8 and Figure 9). As part of this effort, additional data was collected for the purpose of data validation for previous surveys including SHOALS, CHARTS, and USACE cross-sections. Surveys were conducted through a period from April-August 2010. Details of the 2010 hydrographic survey are discussed in Section 2.2.

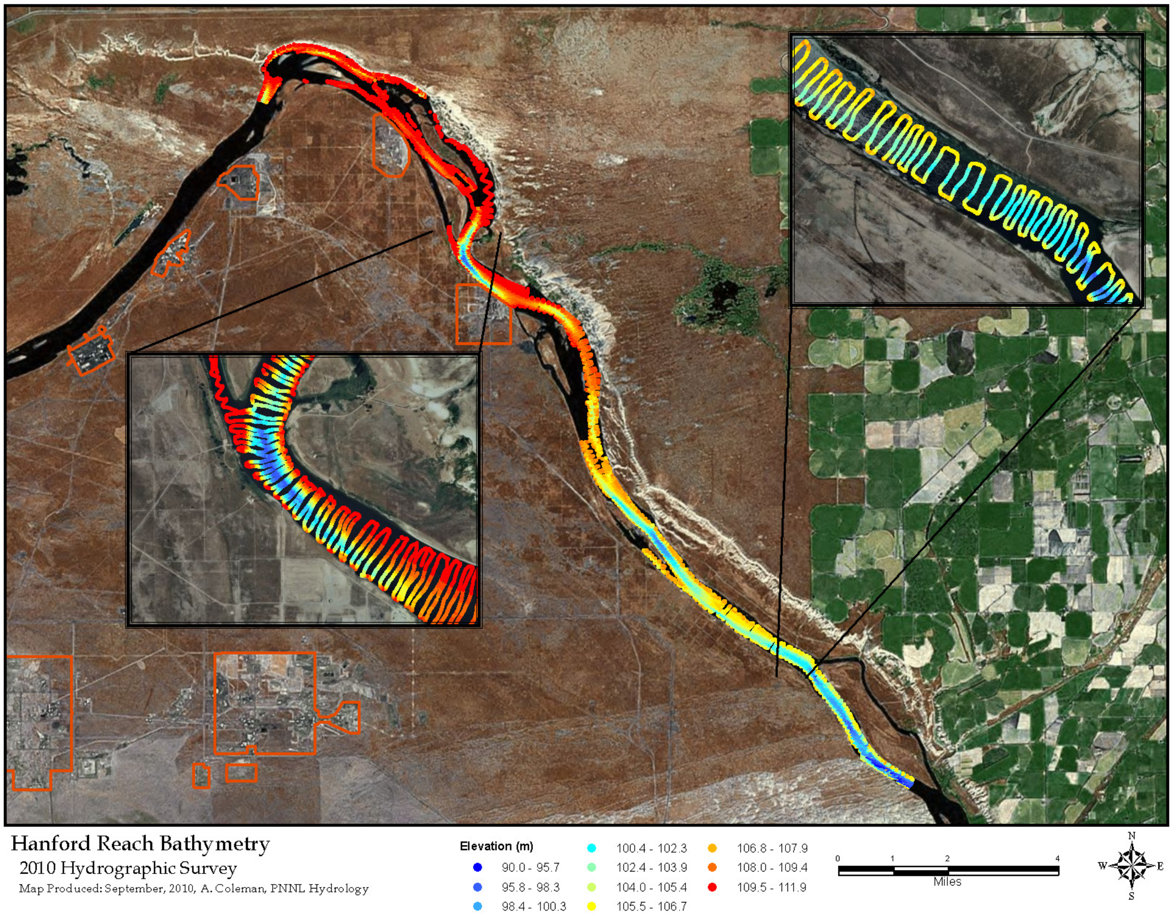

Figure 8. Extent of hydrographic surveys conducted by PNNL in April-August 2010.

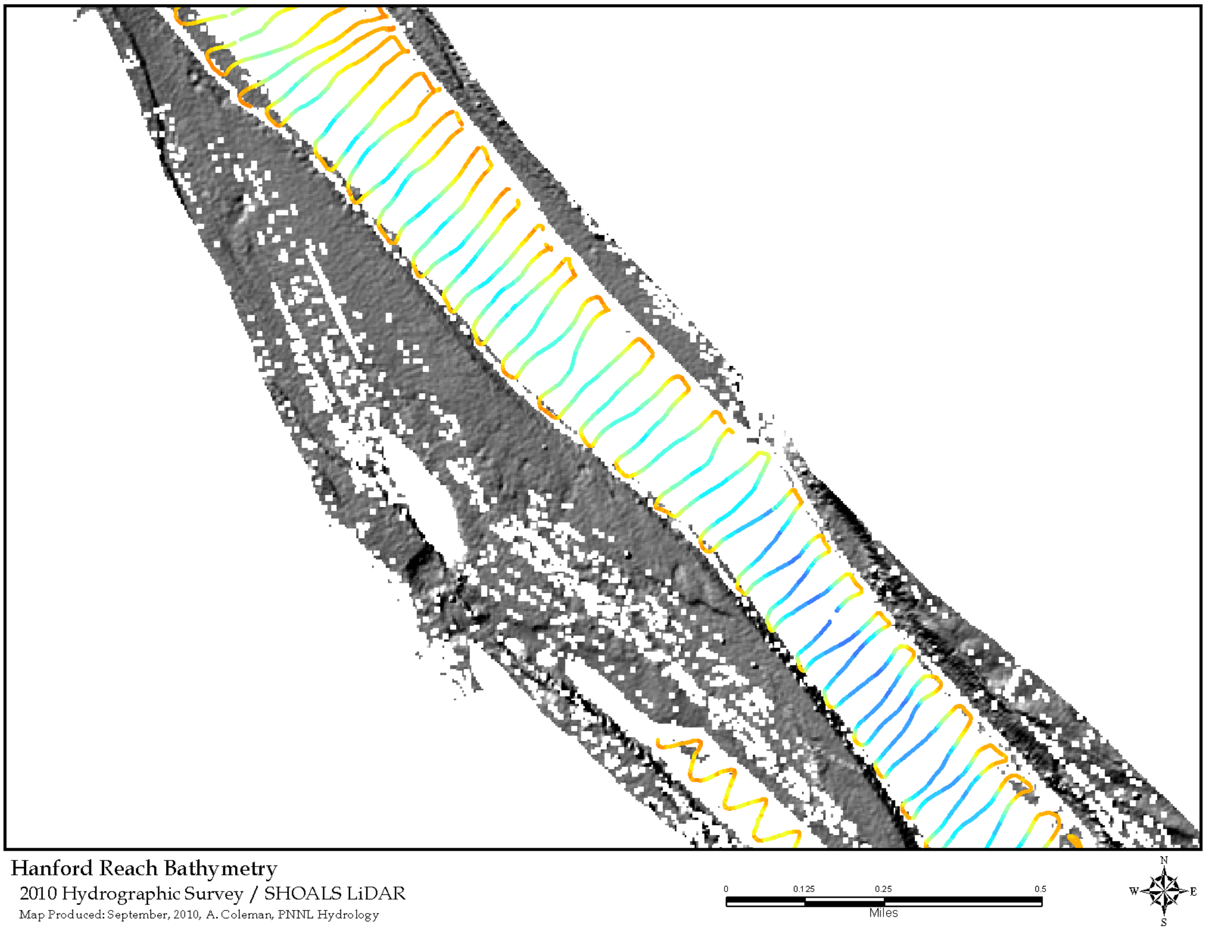

Figure 9. The 2010 hydrographic survey was designed to fill in data holes of the 1998 SHOALS survey. The data holes that could be filled primarily included the deep water areas, as many of the shallow water zones were < 0.5 m deep and not accessible by boat.

2.2 Hydrographic Surveys

A single-beam hydrographic survey was conducted in the central portion of the Hanford Reach from river miles 357 to 377 with the specific intent of filling missing data not covered by the 1998 CHARTS survey and collecting quality control data to compare the current survey with other surveys conducted in the past. The surveys consisted of approximately 890 cross-sections spaced 50-70m apart.

Bathymetric data was collected using an Innerspace 455 single-beam, survey-grade, echo sounder with an 8-degree transducer, operating at 208 KHz, and a manufacturer's stated vertical accuracy of 3.05 cm. Depth data from the echo sounder was collected and saved at a rate of two measurements per second with an average boat speed of 5-7 knots. Horizontal and vertical positioning of the echo sounder was derived using a Trimble 5800 Real-Time Kinematic Global Positioning System (RTK-GPS) providing the most efficient and accurate data possible for the survey. The horizontal and vertical accuracy of the RTK-GPS was calculated to be less than 4 cm and was verified using other known and published benchmarks from the National Geodetic Survey. The RTK-GPS antenna and integrated receiver was mounted on a fixed-length survey pole directly above the echo sounder transducer. The entire echo-sounder/RTK-GPS antenna/receiver package was bolt-mounted to the starboard side of a swim deck on a 23-foot jet boat. The transducer head on the echo-sounder was typically submerged in 0.5m of water, which was deep enough to send and receive a clean acoustic signal. In order to calculate a true bottom elevation, the echo-sounder reported depth and the static survey pole length were subtracted on-the-fly from the synced RTK-GPS elevations. This approach eliminates the need to track and sync fluctuating water surface elevations. Figure 10 illustrates the general system configuration utilized for the hydrographic surveys.

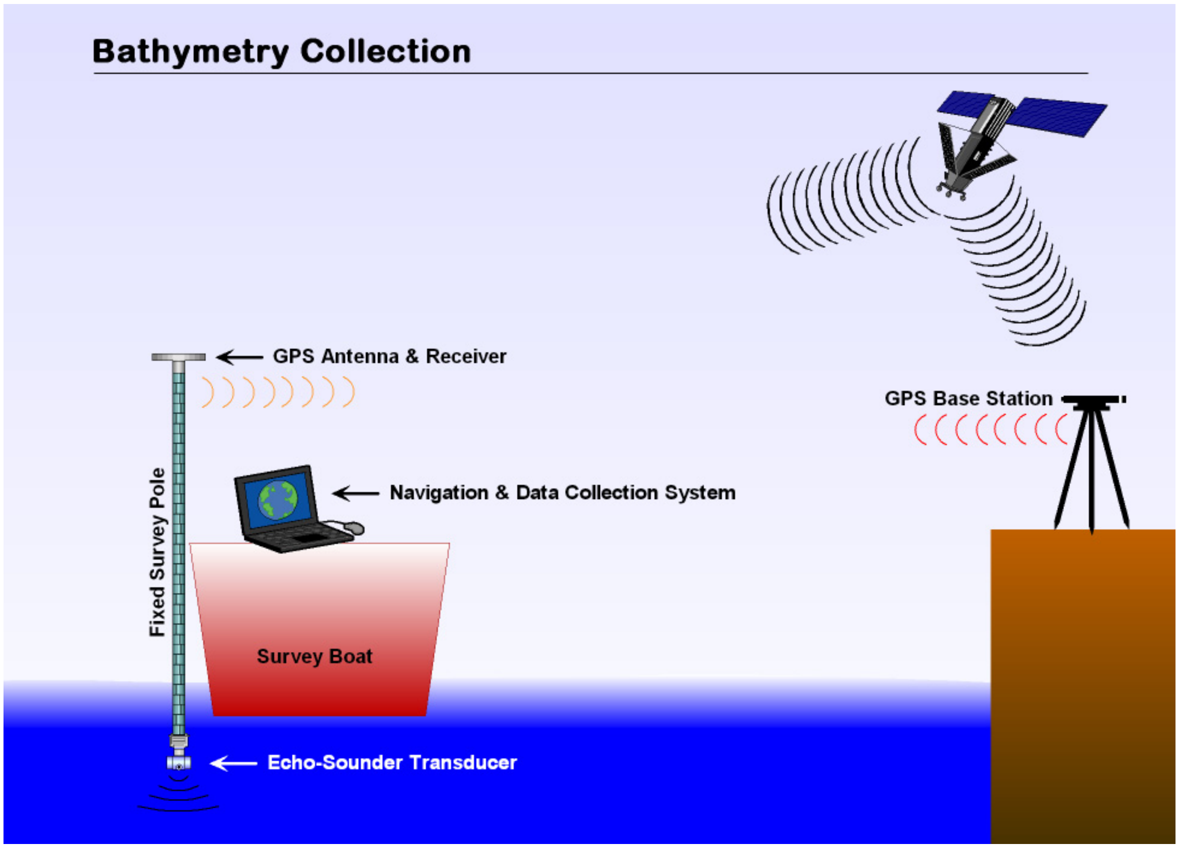

Figure 10. Major components and system setup used in the hydrographic survey allowing for real-time collection and bottom elevation determination.

The pattern to collect the bathymetric data was performed in lateral transects (perpendicular to flow direction) was initiated using a specially generated channel centerline and a Python script that calculates an arc at 90-degrees of the centerline and at user-specified distance interval. These auto-generated cross-sections were reviewed in ArcGIS with 2008 true-color digital orthoimagery and older bathymetry datasets. In some cases the cross-sections were supplemented to capture finer detail around bends or other significant geomorphic features and in other cases cross-section lines needed to be split into multiple segments and angled differently to properly represent multi-directional flows around island features. Additional Python scripts were developed to retrieve the end-point locations of each cross-section and export to a specially formatted file for use in cross-section establishment in the survey/navigation software. Using Trimble's HydroPro real-time navigation and data collection software, the pre-planned transects were loaded and viewed with real-time boat positioning along with underlying orthoimagery and existing hillshaded CHARTS LiDAR bathymetry data. The software not only aids in navigation and collection of required data, but also syncs and stores the depth signal from the echo-sounder to the XYZ triplet coordinate data delivered by the RTK-GPS. The distance between the pre-planned transects was generally setup between 50 and 70m.

All surveys were collected in the following projection:

Projection: Stateplane Washington South, FIPS Zone 4602
Horizontal Units: Meters
Vertical Units: Meters
Horizontal Datum: North American Datum of 1983 (NAD83)
Vertical Datum: North American Vertical Datum of 1988 (NAVD88)
Spheroid: Geodetic Reference System, 1980 (GRS80)

2.2.1 Benchmark setup

One of the most crucial components of a hydrographic survey is the control points used to drive the survey. Several days were spent locating, establishing, and verifying quality near-channel survey control points in the Hanford Reach. Surveys were conducted using a Trimble 5700 RTK-GPS base station and a Trimble 5800 antenna/receiver. The RTK-GPS survey was based on the National Geodetic Survey (NGS) benchmark PID SA1455/ Designation G49 located between the 100-D and 100-H areas (see Figure 11):

Designation: G49
PID: SA1455

Horizontal:	Washington Stateplane South Zone, Meters, NAD83 Northing: 153,347.989 Easting: 575,354.372
Vertical:	North American Vertical Datum of 1988 Elevation: 125.635meters (412.19 feet)

Horizontal Order - FIRST
Vertical Order - SECOND CLASS 0
Ellipsoid Order - FOURTH CLASS II

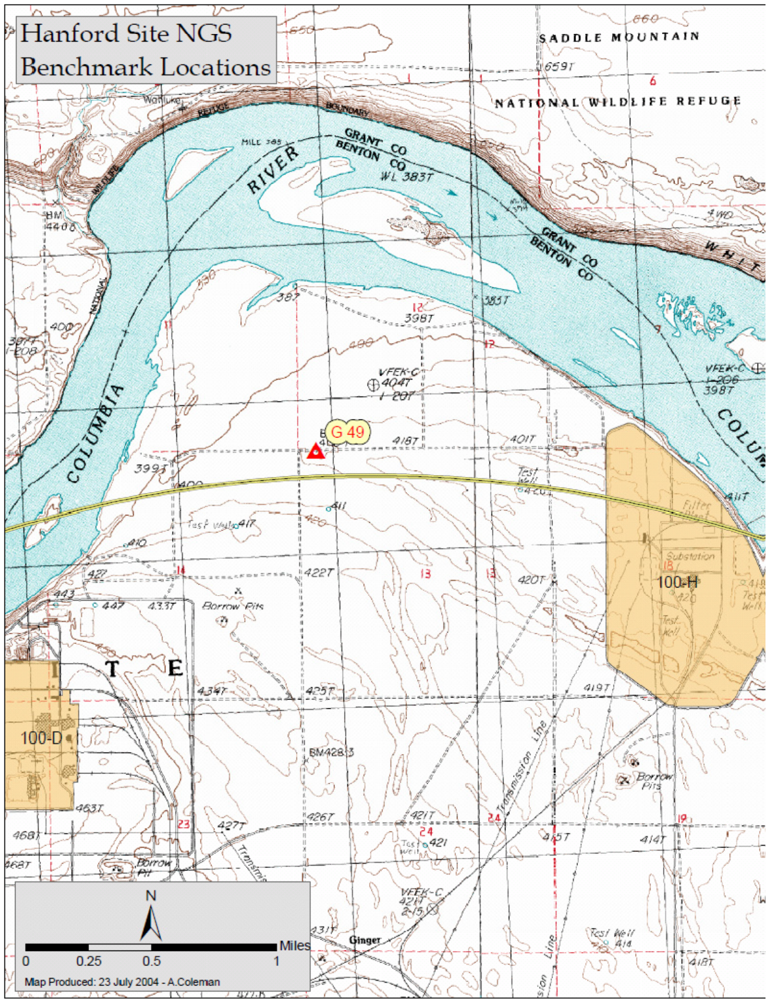

Figure 11. National Geodetic Survey (NGS) benchmark, G49, used to initiate the 2010 hydrographic survey.

The survey setup at G49 was verified to other NGS benchmarks PID SA1711 / Designation Bleakley and PID SA2189 / Designation Gable. In addition, several benchmarks established by the Corps of Engineers were validated for vertical accuracy. Upon the establishment of each new benchmark, a process of setting up the RTK-GPS base station according to published values and collecting QC1 survey values at other nearby published benchmarks was followed. Upon completion of the QC1 survey, the base station was moved to a one the QC1 surveyed benchmarks and the process was repeated, including the original benchmark. This exercise was performed to validate the published data because benchmarks can move and settle over time depending on installation method, soil type, and climate extremes. Survey checks were conducted with every base station setup prior to initiating the hydrographic surveys. The general range of the RTK-GPS is reliant upon a 35-watt radio transmission and is thus limited to about 6-miles. As a result, additional benchmarks were established downstream of G49, validated, and used in a similar manner to what was previously described for QC1 surveys. A benchmark that was located in the central study area was a survey nail located at the White Bluffs boat ramp on a concrete pad (see Figure 12). This benchmark was established using three NGS benchmarks located in the vicinity. All benchmark transfers and pre-hydrographic survey checks had an error of less than 2cm horizontal and vertical.

Figure 12. The White Bluffs survey benchmark was located in the central study area and was used for the majority of the surveys.

2.3 Data Cleaning

Two primary types of data cleaning were used for this project. First, data cleaning was required to filter anomalous data in the raw CHARTS LiDAR survey data and second, a combination of data filtering and 3D editing was required to clean the 2010 hydrographic survey data.

An algorithm was developed to help filter out the majority of bad data points found in the CHARTS LiDAR dataset by using a 3x3 kernel filter to compare individual data points with their surrounding neighbors. In the case that there are extreme differences between a point and some of its neighbors, the data point is eliminated. It was found that in most cases, the bad data points were > +/- 4-meters in elevation from their neighbors. An example of the effect of the initial dataset is shown in Figure 13, results from the automatic data filtering is provided in Figure 14, and Figure 15, provides a dataset with additional hand edits. This same algorithm was used on the CHARTS data. The CHARTS data also exhibited the presence of near-shore riparian vegetation. Because the sources of this data only provided first-return LiDAR data and the 2008 terrestrial LiDAR bare-earth or last-return elevation data was available, thus eliminating the influence of vegetation, the CHARTS data was clipped to include only in-channel elevation data and the newer LiDAR data was merged forming the final dataset.

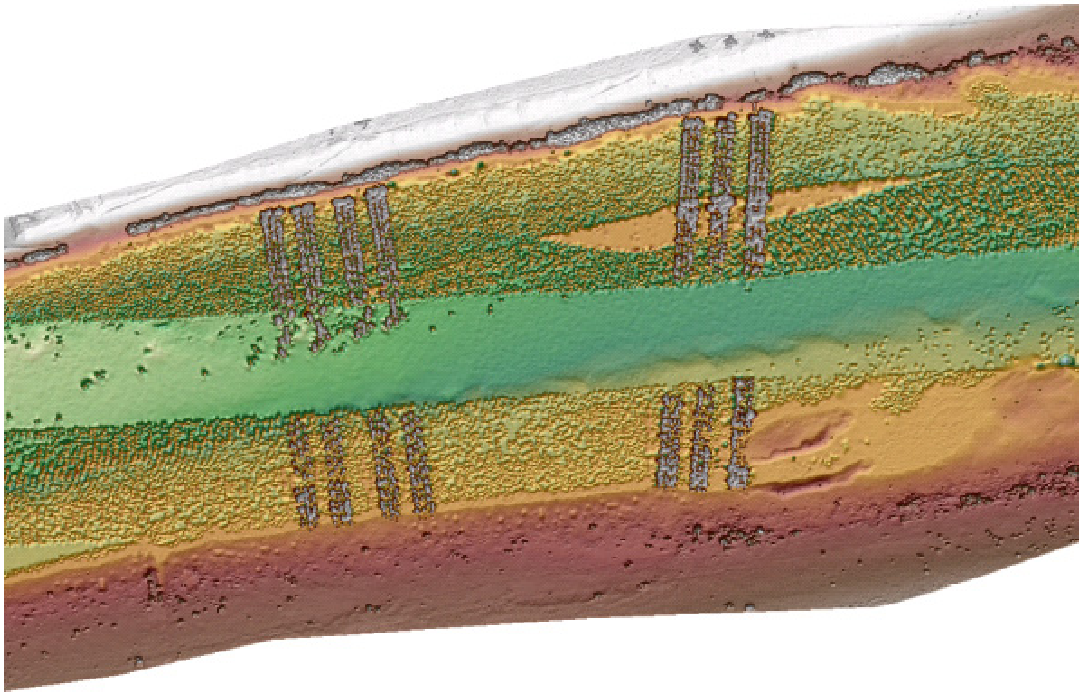

Figure 13. Preliminary CHARTS data showing the presence of bad data points and unwanted data such as power lines crossing the channel area and vegetation clusters in the near-shore areas.

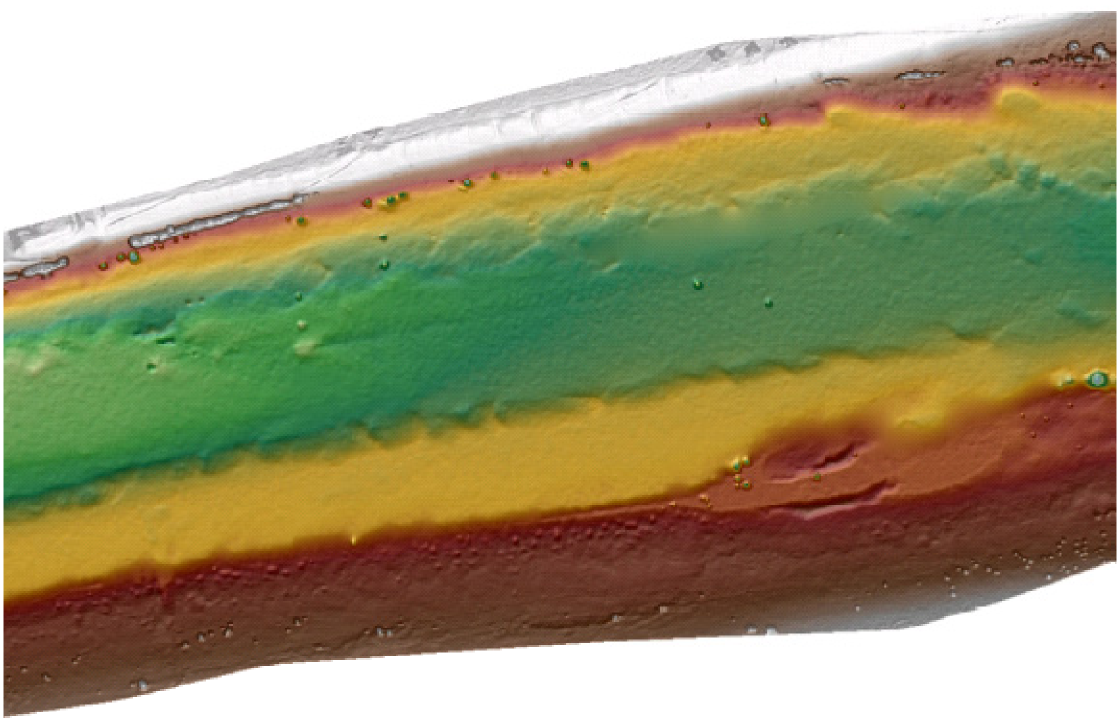

Figure 14. CHARTS data after anomalous data points were filtered out with an algorithm utilizing a 3x3 kernel window and neighbor comparisons. Note the complete removal of the overhead power lines and many vegetation clusters as compared with the preliminary data processing in Figure 13.

Figure 15. After required hand-edits eliminated the few remaining data anomalies the in-channel portion of the raster dataset is finalized. Note that in this figure, only in-channel anomalies were removed; riparian and near-shore vegetation were removed by supplementing last-return terrestrial LiDAR.

The second type of data cleaning was used on the 2010 hydrographic surveys. During the collection of the bathymetry data, the echo-sounder system has some built-in filters to eliminate bad data, however there are cases where air bubbles built up on the transducer head, acoustic echo's are bouncing off of submerged aquatic vegetation such as milfoil, aquatic vegetation has been caught and wrapped around the transducer head, or acoustic turbulence is occurring as a result of cross cutting through high-velocity flows. The initial cleaning process was conducted by using a simple elevation bounds filter to mass eliminate anomalous values. The follow-up process was much more laborious and required visual inspection of the cross-sections in a 3D environment (ArcGIS ArcScene). Visualizing the data in 3D allowed for obvious detection of bad data points which were often characterized by a column of data in a single geographic location. The 3D environment not only allowed visualization of the data, but also selection and removal of data by the analyst. Additional data checks and editing occurred further in the processing chain when using geostatistical methods to fill data between cross-sections.

2.4 Data Processing

A high-resolution (1-m) merged bathymetry and near-shore topography dataset was developed for the Hanford Reach extending from tailrace of Priest Rapids dam to the vicinity of the Interstate 182 bridge, just upstream of the Yakima River confluence, using existing bathymetric and topographic data as well as newly processed hydrographic survey data from 2010.

The entire terrain dataset included approximately 1.85 billion elevation points for consideration and inclusion into the processing of a raster-based three-dimensional topographic/bathymetric surface. The data delivery format of the CHARTS and SHOALS data from USFWS included a large number of ASCII-text files including multiple LiDAR signal return components. A UNIX-based Bourne-shell script was developed to extract and format the CHARTS data for inclusion into a special Geographic Information System (GIS) spatial database. In addition to CHARTS and SHOALS, all other data discussed in Section 2.1 was projected and converted to a common vertical datum for its use in the final processing. Due to the large volume of data to be processed, an open-source spatial database (PostgreSQL/PostGIS) was setup and configured to handle data storage and query statements in a highly-efficient manner. Unfortunately, using the industry standard tools and methods, an effort such as this would have been difficult and inefficient. A total of 57 computational processing tiles were established over the Hanford Reach and incorporated at least 100m overlaps to help achieve seamless data transitions during the final mosaicking of the processed tiles.

Once the raw data was extracted into computational tiles, several processing steps took place to achieve a final raster-based surface. The CHARTS survey provides continuous coverage therefore, outside of the editing functions already discussed the data is ready for use. An important consideration in dealing with the mixed datasets from CHARTS, SHOALS, and the terrestrial LiDAR data, was that SHOALS data captured vegetation clusters on the riverbanks, whereas with the CHARTS and the 2008 terrestrial LiDAR, these data could be screened out using a subset of the LiDAR returns, referred to as the last-return, which gives actual ground-level elevation. To eliminate the vegetation clusters in the near shore areas, the terrestrial LiDAR was first used to extract a river shoreline boundary based on the LiDAR return signal. Once this boundary was established, the SHOALS data was clipped so that only bathymetric data would be included, and the terrestrial LiDAR would cover non-watered areas, effectively removing vegetation clusters. For areas outside of the Hanford Site, particularly adjacent to the city of Richland, vegetation clusters still remain in the data and need to be removed by a mixture of a raster-filtering algorithm and manual point removal.

The primary focus of the data processing effort revolved around the geostatistical processing of data in-between the newly collected channel cross-sections. While efforts were made to create a reasonably dense network of cross-sections through the central Hanford Reach, using a single-beam echo-sounder is limited in its spatial coverage. The use of a multi-beam system, where a push-broom style of data collection provides more consistent data coverage, would have been ideal, however it is also costly to operate and more difficult to use and calibrate in a dynamic open-channel river environment with varying velocity and temperature profiles.

To begin the process, using the cleaned hydrographic data and the CHARTS in-channel elevation data, and high-resolution orthoimagery, ArcGIS ArcMap was used to develop a total of 44 processing tiles for the central Hanford Reach. The designation of the processing tiles was based on the overall premise of available data and sections of river with similar flow orientations. For areas around Locke Island, this required generating a series of small tiles that represent the alternating flow orientations around the island complex. The longitudinal orientation of the processing tiles was based on a 20-meter buffered shoreline dataset derived from the 2008 terrestrial LiDAR dataset. It was also imperative that the processing tiles contain overlapping boundaries. The overlap boundaries were largely dependent upon underlying cross-section data and typically include two cross-sections shared with an adjacent tile. This ensures smooth transitions between tiles when processing the final dataset. A pre-processing script was developed to retrieve all data from within the tile boundary and convert the GIS-based point data to XYZ triplets in a comma-delimited ASCII file. The use of 10-meters of near-shore topography and existing in-channel CHARTS data helps to inform and constrain the geostatistical processing between cross-sections. While methods including nearest neighbor, thiessen polygon/triangulated irregular network (TIN), inverse distance weighting, splines, and kriging are commonly used, there is some difficulty in getting accurate results because the changing channel morphology does not necessarily fit the capability of the geostatistical prediction method. In 2004, PNNL implemented a method that has shown favorable results for sampling between channel cross-sections that uses anisotropic ordinary kriging, specifically accounting for directional influence in the channel morphology. The use of anisotropic ordinary kriging in bathymetric processing has been found to minimize typical sinkhole, hillock, and other anomalous effects that are commonly found when processing transect data using more common methods such as nearest neighbor and TIN.

In general terms, ordinary kriging is an efficient, flexible, and accurate method for gridding irregularly spaced data. There are weights established in the kriging process using spatial correlation and distance between both the observation points and the predicted points. The use of anisotropy in conjunction with ordinary kriging allows us to take advantage of stream-wise channel morphology. The overall geomorphic structure of a river channel is driven by direction of flow, making a method such as this useful. For this data development process, the anisotropic ordinary kriging technique was implemented to create a continuous surface between cross-sections and provide an additional dataset (i.e., the missing data areas in the CHARTS zone) for the final surface generation. The ordinary anisotropic kriging method is also seen in the literature as "range anisotropy" and requires the use of a two-dimensional semivariogram model to generate the required kriging weights (see Figure 16) (Eriksson and Siska, 2000). While the complete algorithm and terms can be found in Eriksson and Siska (2000), for the purposes of this discussion, a basic definition of the major terms are presented. The values x and y are the rectangular coordinates in easting and northing, respectively, Δx and Δy, is the change in coordinates through the sampling space of the ellipse, u and v define the coordinates oriented along the major and minor axes of the ellipse that are converted from rectangular coordinates to polar coordinates and achieves ξ, is the separation angle of u and v relative to its rectangular coordinates (i.e., the direction), p'_i *and* p'_j are the origin and target points, h is the lag distance, Φ is the separation angle in the ij coordinate space, and a_{min} and a_{max} define the anisotropic magnitude.

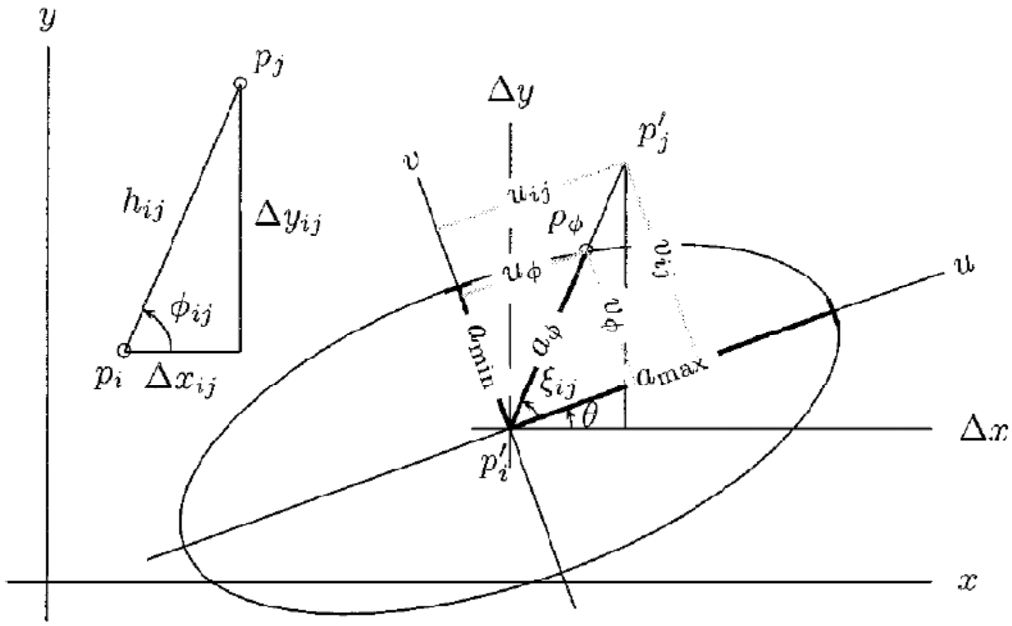

Figure 16. A range anisotropic ellipse variogram model used in the 2010 bathymetric data processing (Eriksson and Siska, 2000).

The anisotropic weights defined above are calculated as a function of an ellipse angle and the range/distance to determine trends in the data. For each processing tile, an empirical semivariogram model was established to help determine proper ellipse ratio, a_{min} and a_{max} , and angle terms. This parameter-estimation procedure allows the data to inform itself on the orientations showing the strongest data trends. The outcome of this procedure provides a regularly gridded point dataset and a set of interval-defined contour lines. The key to using ordinary anisotropic kriging in this type of setting is generating logical tiles for the processing, rather than processing the Hanford Reach as a whole. Each stream section that was processed was verified for conformity with adjacent sections. This process rarely had issues since each processing tile shared one or two cross-sections with adjacent tiles. A data review of the gridded and contoured data immediately revealed suspect data points, which were eliminated in the source data and the kriging process was repeated. Once the gridded datasets were finalized, these data were converted into GIS point files. The kriged data were subset using a developed mask polygon of the river channel that only includes the data gap areas from the SHOALS collection (see Figure 17). These data were incorporated into the master elevation database used to generate the final merged bathymetric/topographic elevation surfaces.

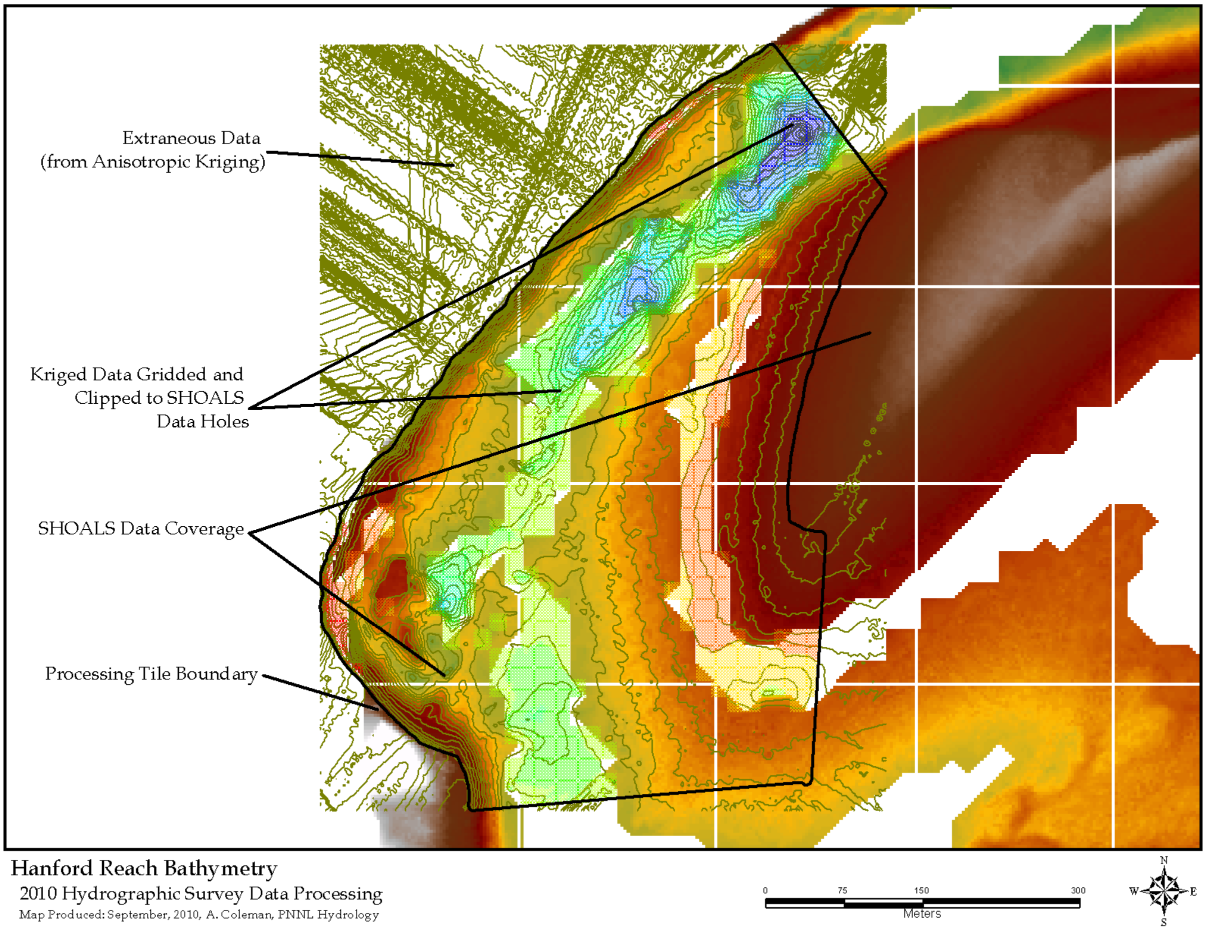

Figure 17. An example of the results from a processing tile where an anisotropic ordinary kriging point grid is clipped to the data gaps in the existing SHOALS LiDAR data.

For the final stage of the data development effort, a state-of-the-art finite difference, locally adaptive, discretized thin-plate spline terrain algorithm by Hutchinson (1996, 2000, 2009) was used and implemented on a series of RedHat Enterprise Linux v.5 high-performance servers. This terrain algorithm responds very well to sharp changes in terrain and is well-suited to handle very large datasets. A series of parameters is required to adjust the characteristics of the data and output data. A series of codes were developed to: 1) gather all required and finalized datasets in ASCII XYZ triplets and format the data to a pre-specified column defined, tab delimited input file; 2) generate initial basic parameters that determine the geographic extents and the min/max elevation range of the multi-billion point datasets; and 3) auto-generate the final required parameter file including the above determined geographic extents, but also, data types, source error assessments, processing iterations, and barrier and roughness tolerances, all of which control the development, algorithm/processing behavior, and of course, the final outcome of the terrain model.

3.0 Data Integrity

In order to test the data quality of the existing data with the new hydrographic surveys, quality assurance (QA) points were collected and evaluated against other data. This serves the purpose to understand the quality of the survey in comparison to other data collection efforts. In addition, an inter-survey comparison was made from day to day surveys, overlapping previously collected data to ensure the current survey was consistent.

3.1 Terrestrial LiDAR

An early QA analysis was conducted on the 2008 terrestrial LiDAR data to ensure its integrity before including it into the overall processing. This type of QA analysis is particularly important when merging disparate datasets, as in this case, merging topographic LiDAR collected from one instrument and bathymetric LiDAR from a separate instrument using two independent surveys at two different points in time. To conduct the QA analysis, the elevations from three terrestrial LiDAR tiles were compared to PNNL field surveyed elevations in the vicinity of 100-D. The 100-D area was chosen because of the high-quality detailed survey data, as well as the variety of terrain from flat to very steep slopes. It is generally expected that data comparisons on steep slopes will not correlate as well as on flat terrain. Three LiDAR tiles were used that were coincident with 4,697 points in the surveyed elevation data (see Figure 18). The survey data points were overlaid on the LiDAR 10-centimeter grid and the coincident LiDAR elevation values were collected and stored to the attribute table of the survey data. This approach allows a direct comparison between survey elevation values and LiDAR elevation values. The mean offset between the field surveyed elevations and LIDAR-derived elevations was 6 millimeters with a standard deviation of 10 millimeters. The correlation coefficient between the 4,697 field survey elevations and LiDAR elevation was R^2 0.9998 with a root-mean-square error of 1.1 millimeters (see Figure 19).

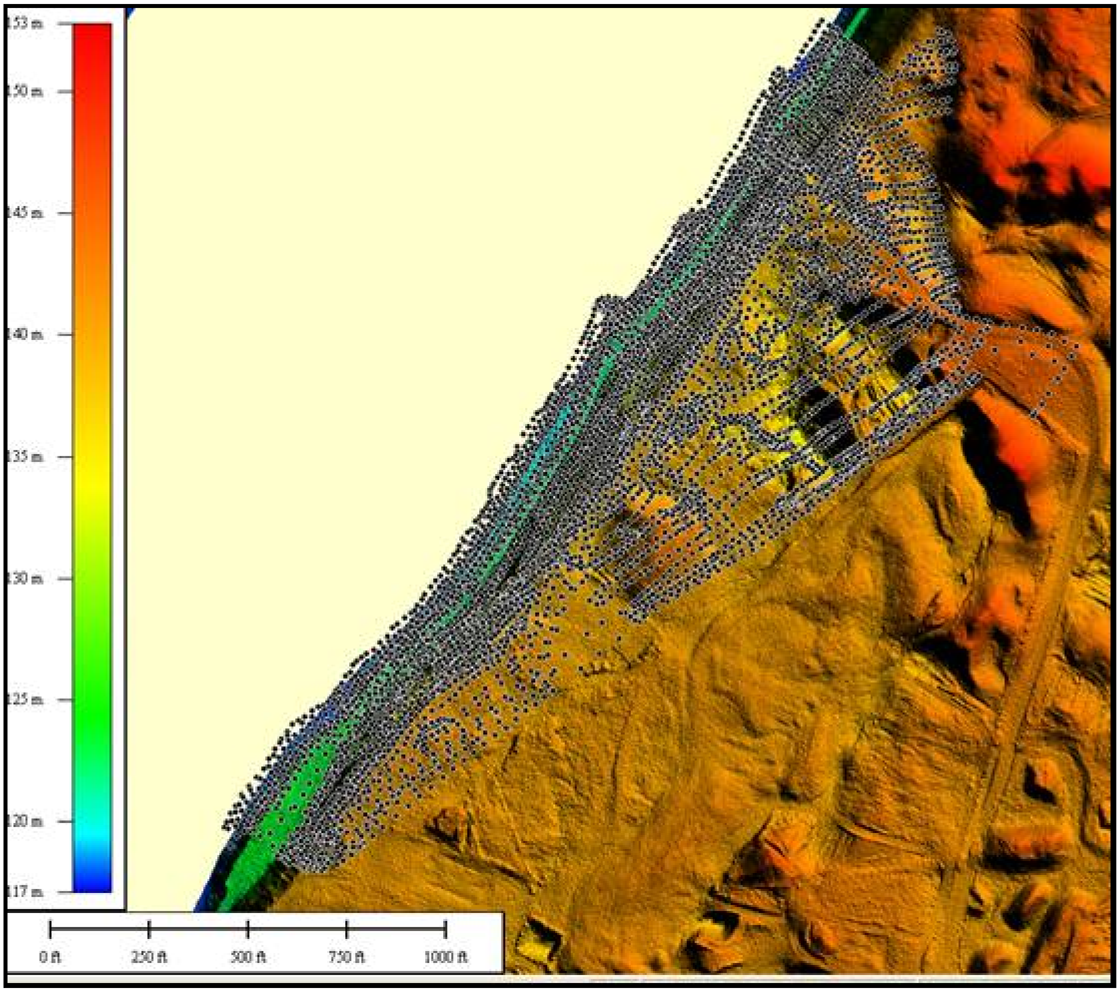

Figure 18. High-quality survey data in the 100-D area was used to QA the 2008 terrestrial LiDAR data.

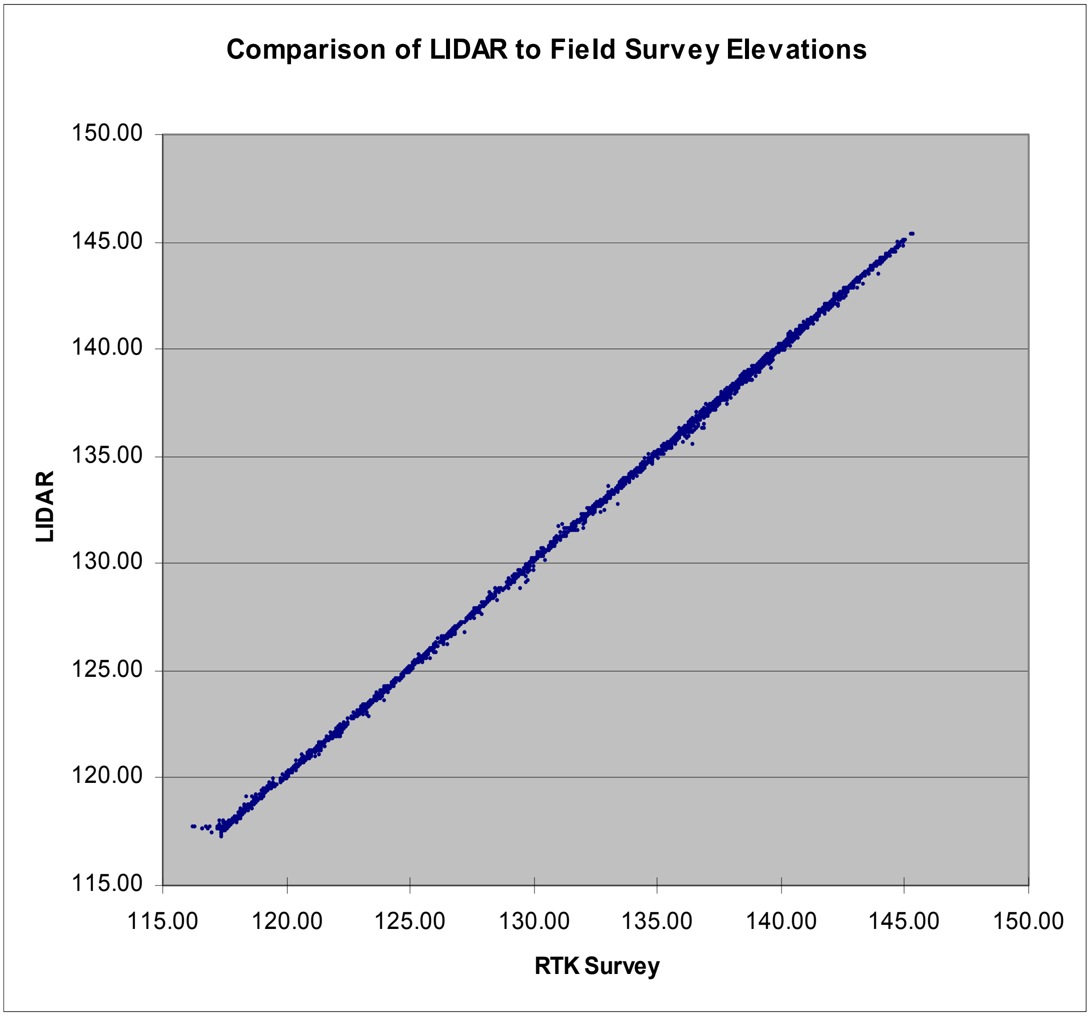

Figure 19. Scatterplot of field survey elevations versus LiDAR elevations reveals a high data agreement with an R^2 of 0.9998.

3.2 Hydrographic Survey Assessment

The hydrographic surveys conducted in FY2010 were intentionally collected in areas that overlapped coverage in the 2003 CHARTS LiDAR survey, the 1998 SHOALS LiDAR survey, and USACE cross-sections. A comparison was made with each of these sources as a means to understand the degree of difference between the varying data. It should be noted that the QA assessment reported here was conducted after initial edits to the 2010 hydrographic survey data. Additional data edits were made after the QA assessment reported here as errors were identified through contouring and gridded hillshade review of the data. In short, the final data product is improved upon what is reported here. Overall, the comparisons between the 2010 hydrographic survey and the other data sources was favorable and is discussed here.

The initial assessment was conducted on with USACE cross-section data collected in the 1980's. Because the 2010 hydrographic surveys and USACE cross-sections weren't always located along the same transects, a procedure was developed to retrieve each USACE elevation point and find the nearest

2010 hydrographic survey point within a maximum distance of 10 meters. The resulting sample size yielded 231 points for comparison. The resulting analysis yielded an R^2 value of 0.97 with a mean difference in elevations at 0.61 m. Figure 20 illustrates the correlation.

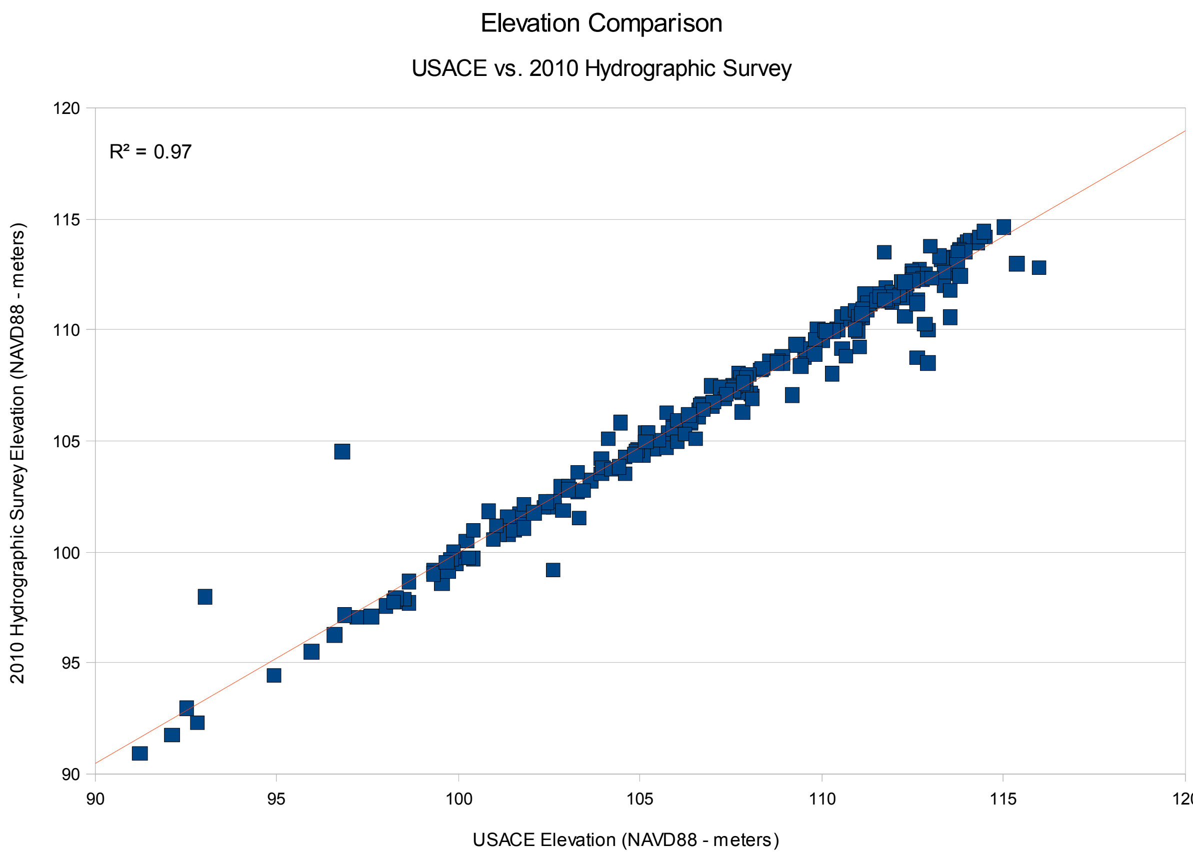

Figure 20. Correlation of elevations between USACE cross-section data and the 2010 hydrographic survey.

Total Sample Size: 231
Mean Difference: 0.61 m
Max Difference: 7.71 m
SD: 2.95 m
$R^2 = 0.97$

The data used in the assessment was the 2003 CHARTS LiDAR data. Because of the continuous CHARTS coverage through the channel, a direct point to point comparison could be made with this data. Data was specifically collected to conduct this assessment and to understand the quality of both datasets. A sample size of consisting of 2,816 points were evaluated. The resulting analysis yielded an R^2 value of 0.93 with a mean difference in elevations at 0.88 m. Figure 21 illustrates the correlation.

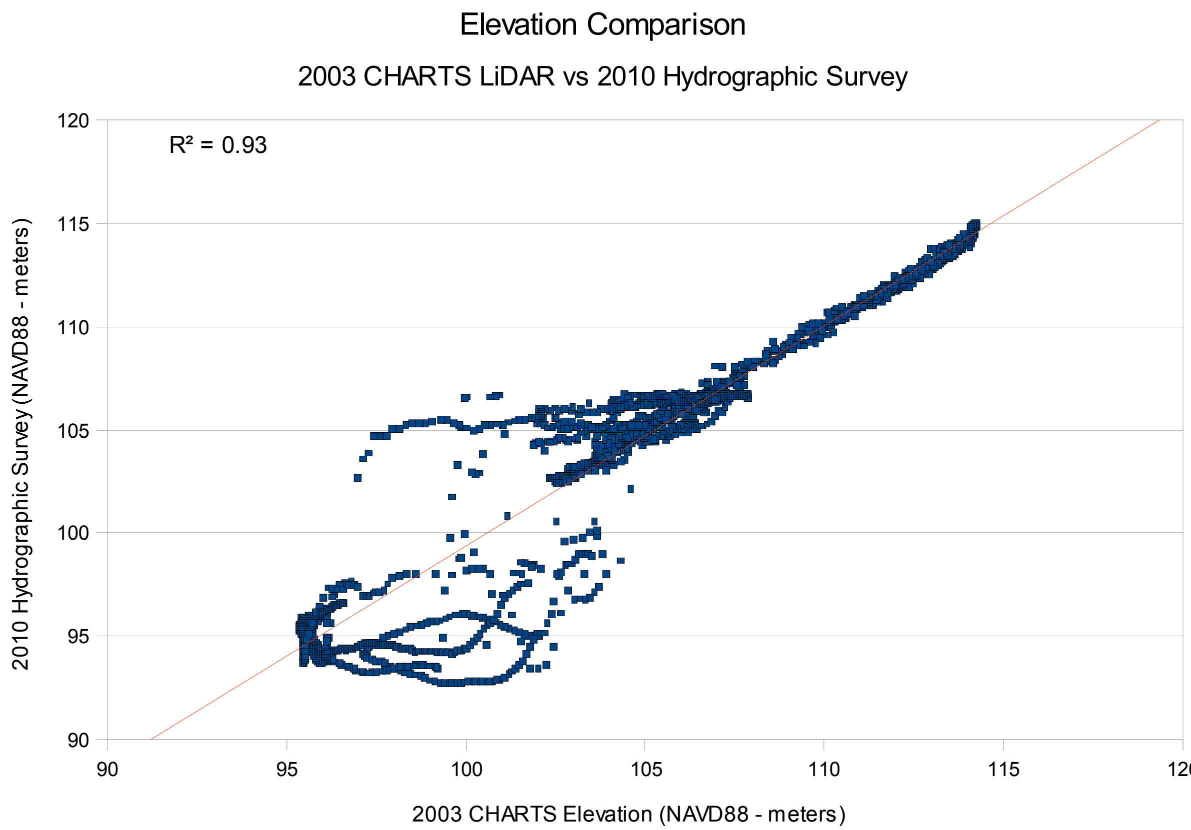

Figure 21. Correlation of elevations between 2003 CHARTS LiDAR data and the 2010 hydrographic survey.

Total Sample Size: 2,816
Mean Difference: 0.88 m
Max Difference: 8.64 m
SD: 1.55 m
$R^2 = 0.93$

Finally, the largest dataset used for this analysis was the 1998 SHOALS LiDAR and was particularly important since this covers the central area of the Hanford Reach where the hydrographic surveys were required. A sample size consisting of 38,065 points were evaluated. The large number of sample points represents the frequent overlap the hydrographic surveys had with the SHOALS data. The data for the analysis was gathered by doing one to one XY coordinate matching and comparing elevation values. Initially, the entire hydrographic survey was used in this procedure. Once the comparisons were made, all null data values were eliminated, since these were areas where SHOALS data was missing. The resulting analysis yielded an R^2 value of 0.96 with a mean difference in elevations at 0.35 m. Figure 22 illustrates the correlation.

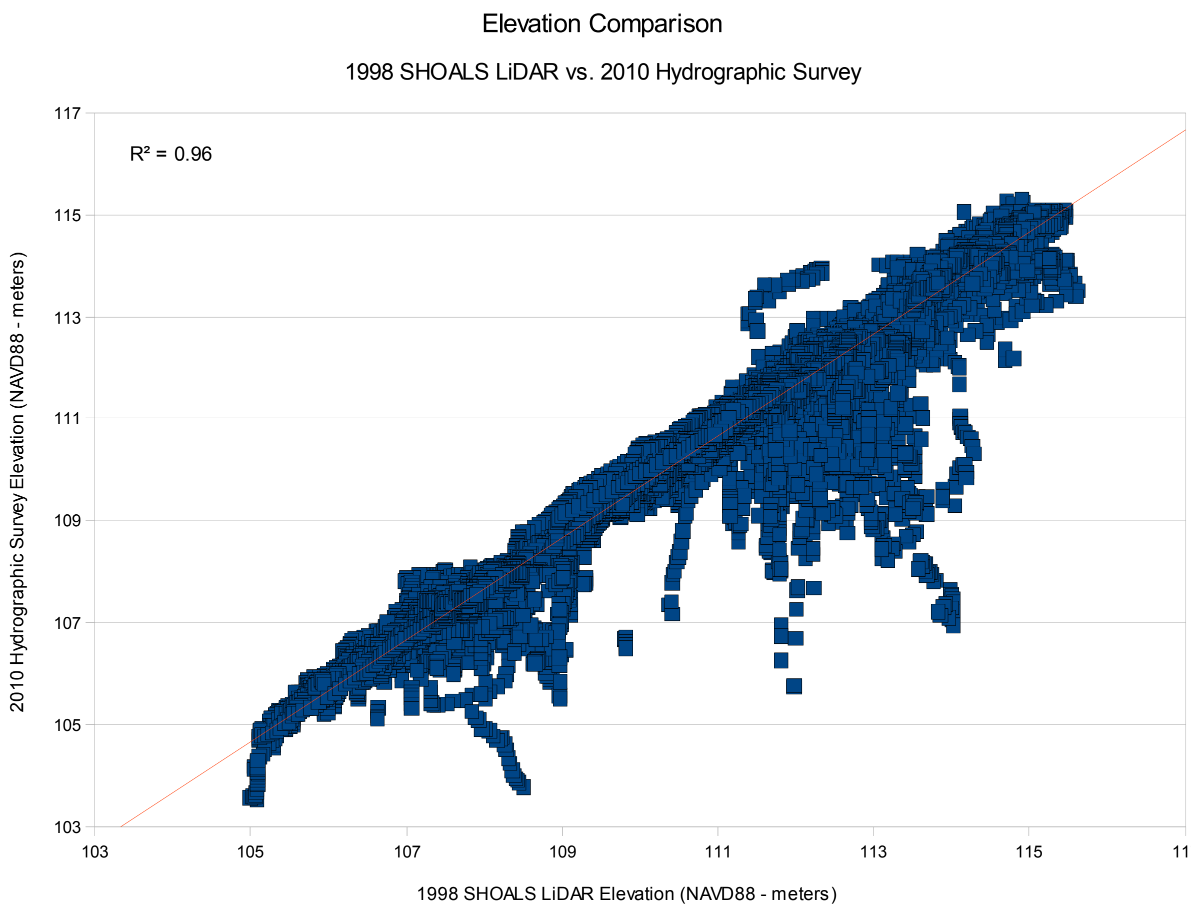

Figure 22. Correlation of elevations between 1998 SHOALS LiDAR data and the 2010 hydrographic survey.

Total Sample Size: 38,065
Mean Difference: 0.35 m
Max Difference: 7.08m
SD: 0.47 m
$R^2 = 0.96$

4.0 Data Dissemination

The dissemination of the final merged bathymetry/topography dataset along with other relevant datasets such as the 2008 7 cm pixel resolution true-color/color-infrared orthoimagery and the entire set of full resolution 2008 topographic LiDAR for the Hanford Site, need a modern and efficient mechanism to distribute these large datasets. For example, the final suite of processed bathymetry/topographic data developed for this project is approximately 60Gb, the 2008 true-color and color infrared imagery is sized at 750 Gb, and the 2008 topographic last return LiDAR is approximately 550Gb. While the data dissemination of the resulting data is not a part of the original work scope on this project, the efficient use of the budget allowed for the development of this capability making the data readily available and usable by all with a demonstrated need. This work also demonstrates the first working and tangible solution to meet the needs and objectives of the Hanford Geospatial Information Strategy and Implementation Plan (Rush et al. 2010). This plan states "...in the current environment, no formalized avenue of collaboration exists other than a statement of work between contractors." The implementation put forth by PNNL provides an operational model of data dissemination that can be implemented for the proposed centralized or distributed data clearinghouse that becomes the record copy of current and historic datasets for the USDOE Hanford Site. The PNNL geospatial data services implementation provides direct server connections to a series of geospatial databases through a direct ArcGIS Server connection, and the Open Geospatial Consortium's (http://www.opengeospatial.org) standard protocols of Web Coverage Service (WCS) image services and Web Map Service (WMS). The WCS and WMS protocols are open standards and are accessible by both commercial and open-source GIS platforms as well as directly through a web-browser interface.

Currently, the PNNL implementation has been constructed across two servers to meet objectives in computational efficiency and security. “Server A” is inside the PNNL firewall and hosts and broadcasts the spatial database and is based on a 64-bit hardware and software configuration that includes:

1. Windows Server 2003 R2 SP2 64-bit operating system
2. Microsoft SQL Server 2005 x64 SP3 (relational database)
3. ESRI’s ArcGIS Server/ArcSDE v. 10.0 (spatial database engine)
4. Mixed geodatabase v.9.3.1 and v10
5. 14 Tb of RAID5 storage

“Server B” is in the PNNL extranet outside of the PNNL firewall and is responsible for the web-hosting services and spatial database access back to “Server A” over secured ports. This setup is also based on a 64-bit hardware and software configuration that includes:

1. Windows Server 2008 SP2 64-bit operating system
2. Internet Information Services IIS 6.0 (web services)
3. Apache/Jakarta Tomcat 6.0.29 (JAVA servlet containers)
4. JAVA JDK 6.0 Update 21 (JAVA development environment to support JAVA web services)
5. ESRI ArcGIS Server 10.0 (web server service that provides full ArcGIS functionality to websites)
6. Microsoft SQL Server 2005 x64 SP3 (relational database)
7. ArcMap v. 10.0 – (map authoring for running as a map service with ArcGIS Server)
8. Geodatabase v.10

Details on the direct connection to ArcGIS services can be found in Appendix B. Web-based interface can be accessed via the following the following URL: http://gisx.pnl.gov/gisx/services/HIMG_2008_Bathymetry/ImageServer/WCSServer?

An interactive map display with this and other relevant imagery data can be accessed here: http://gisx.pnl.gov/hanfordimg/default.aspx

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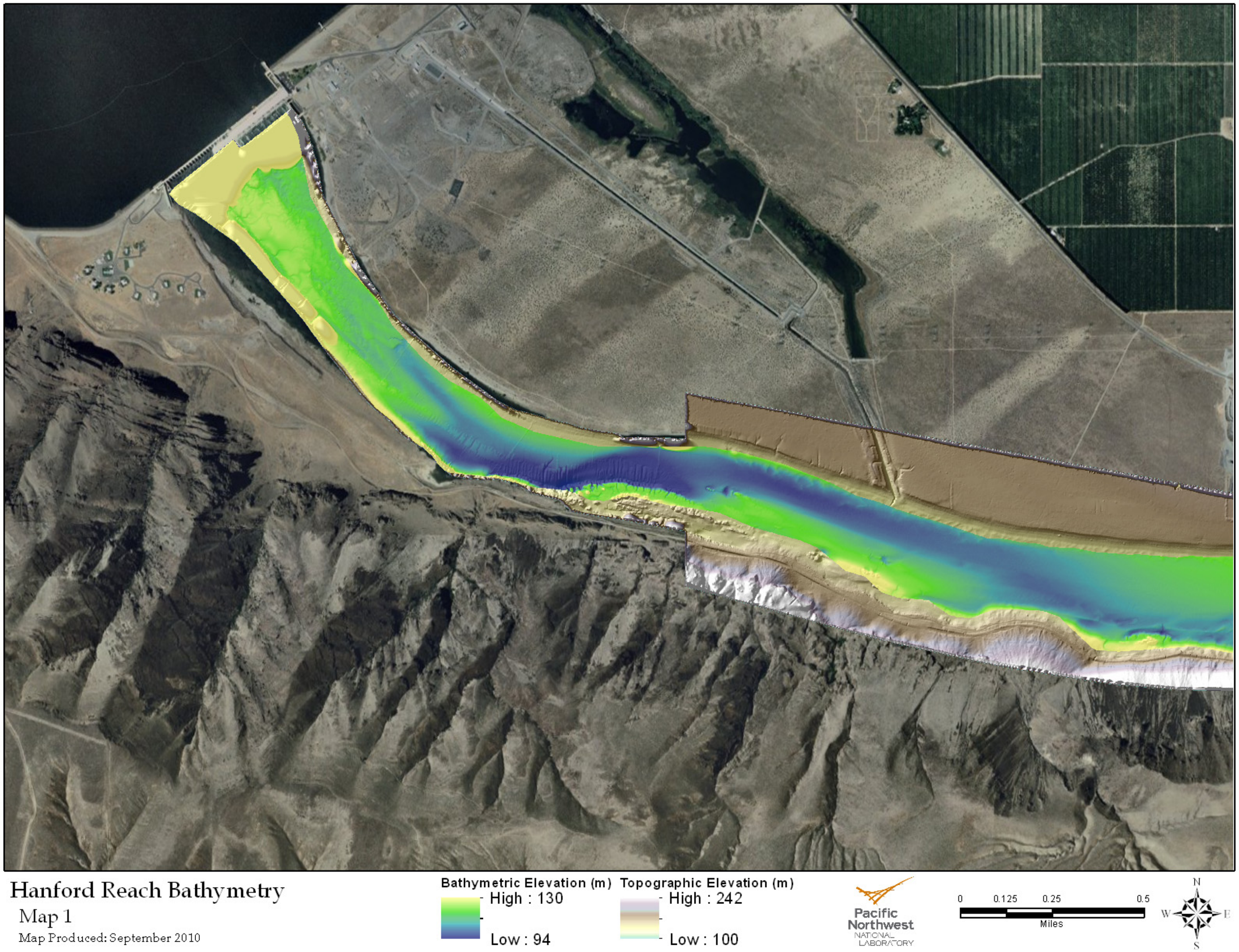
Appendix A

Bathymetry Maps


Hanford Reach Bathymetry
Map 1
Map Produced: September 2010
Bathymetric Elevation (m)
High : 130
Low : 94
Topographic Elevation (m)
High : 242
Low : 100
Pacific Northwest
NATIONAL LABORATORY
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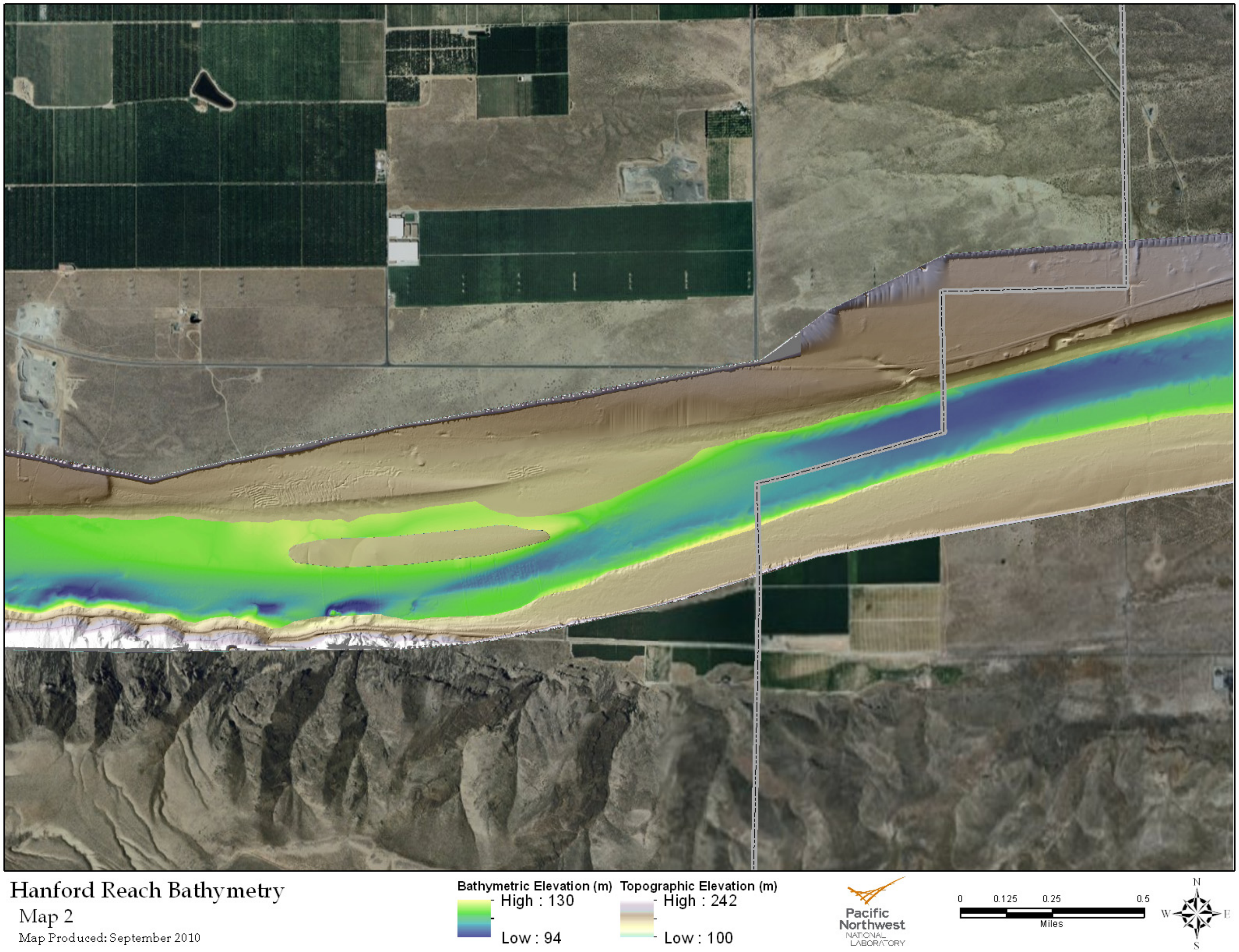

Hanford Reach Bathymetry

Map 2

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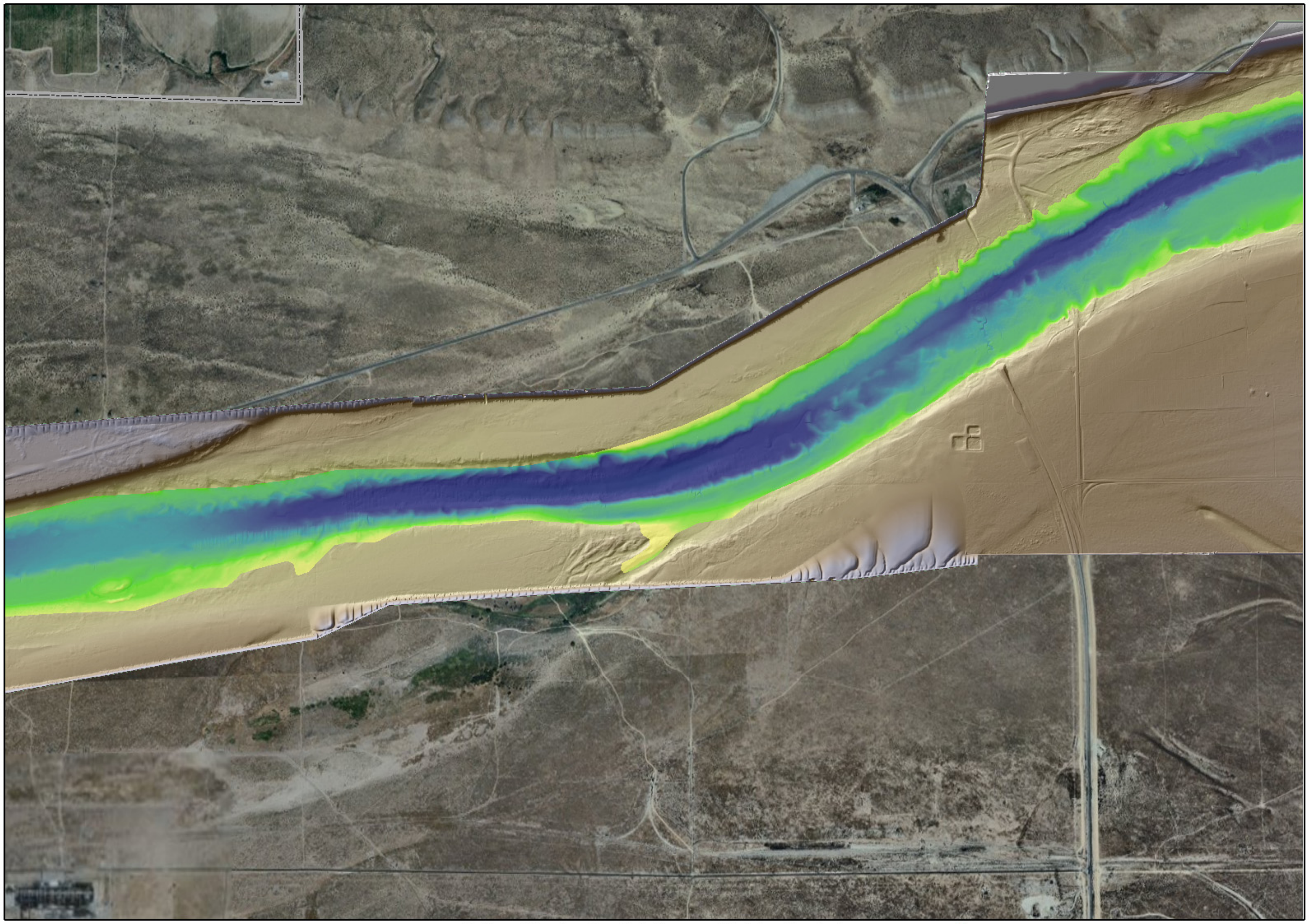

Hanford Reach Bathymetry

Map 3

Map Produced: September 2010

Bathymetric Elevation (m)
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Low : 94

Topographic Elevation (m)
High : 242
Low : 100

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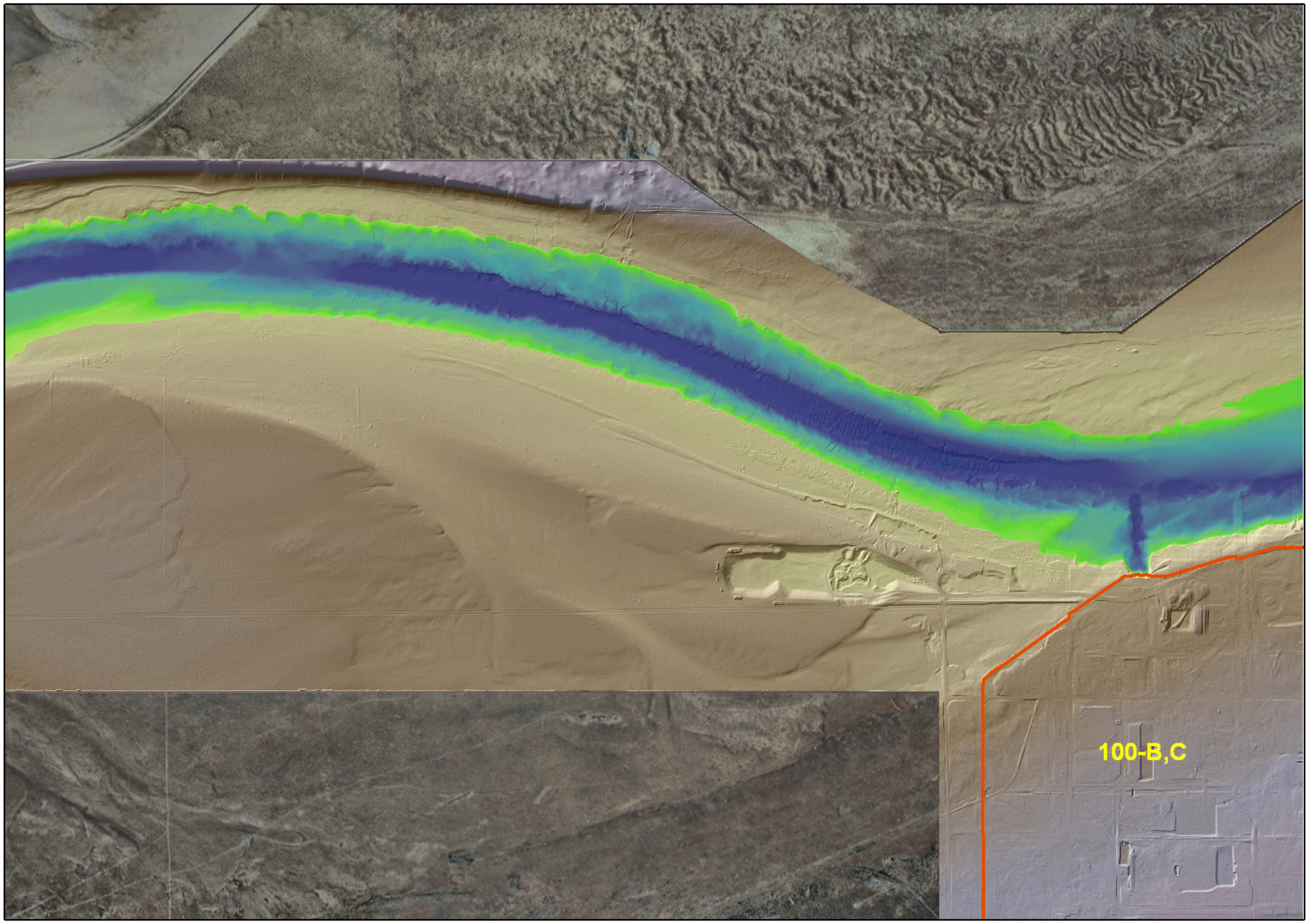

Hanford Reach Bathymetry

Map 4

Map Produced: September 2010

Bathymetric Elevation (m)
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Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

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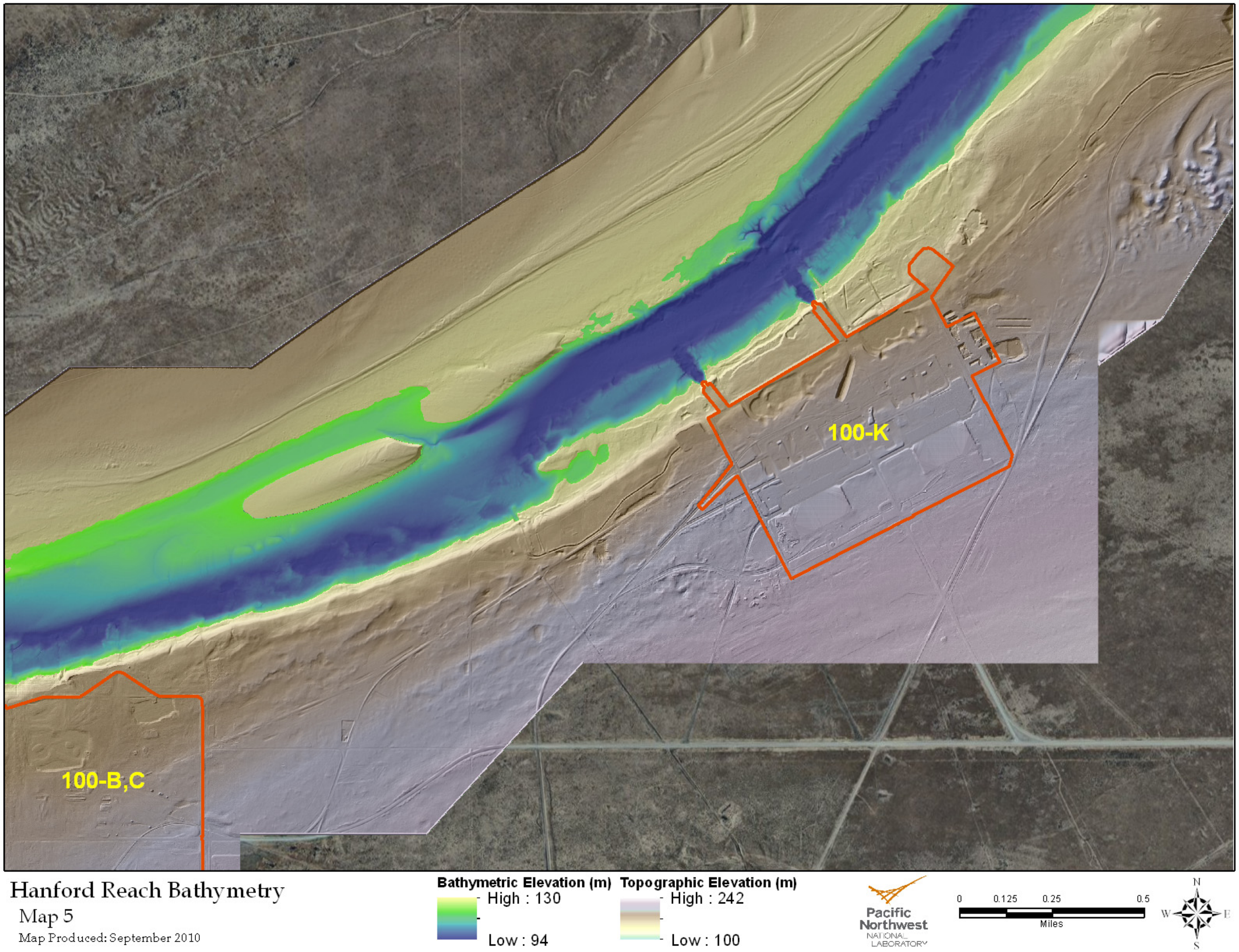
100-K
100-B,C
Hanford Reach Bathymetry
Map 5
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Low : 94
Topographic Elevation (m)
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Low : 100
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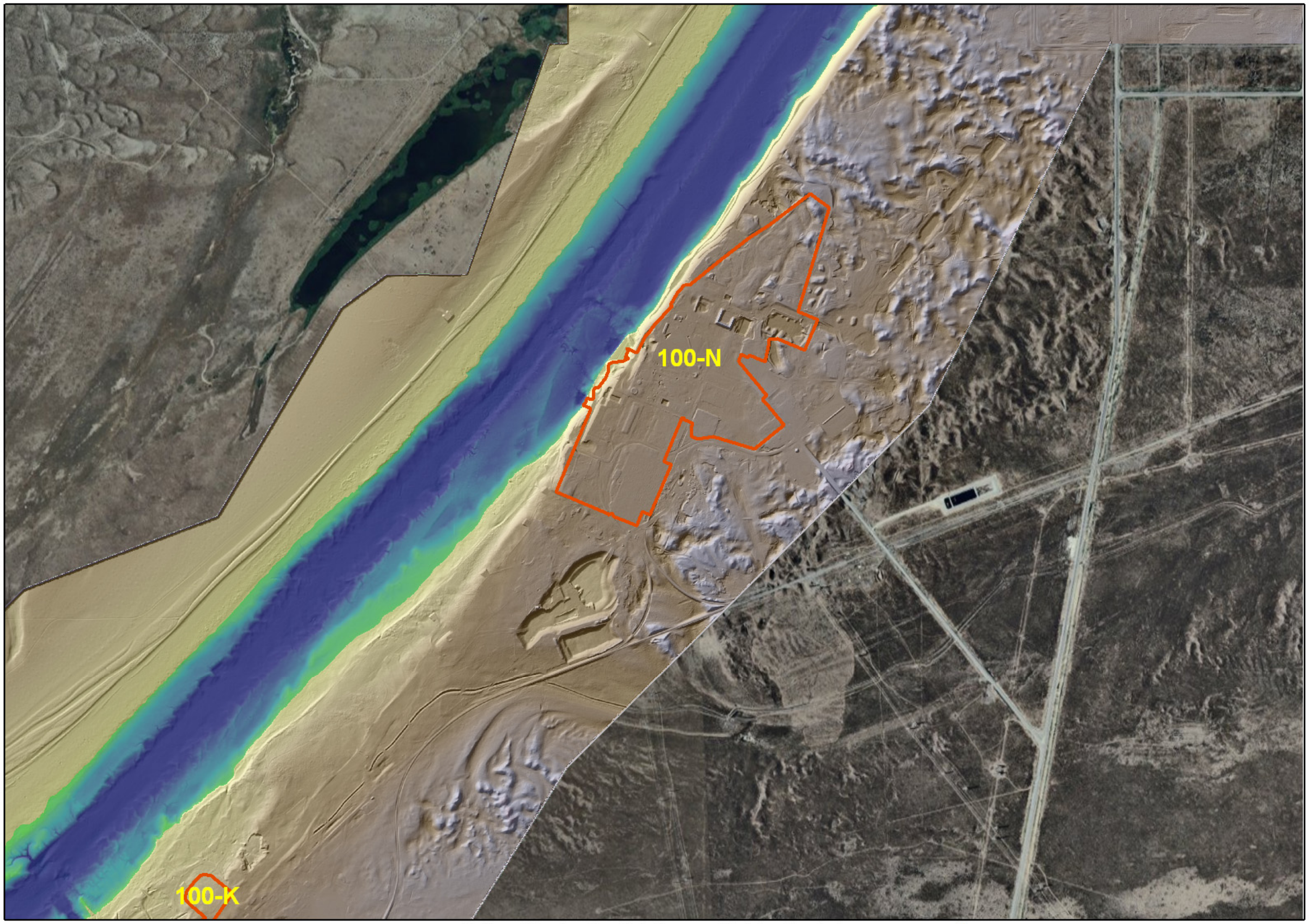

Hanford Reach Bathymetry

Map 6

Map Produced: September 2010

Bathymetric Elevation (m)
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Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

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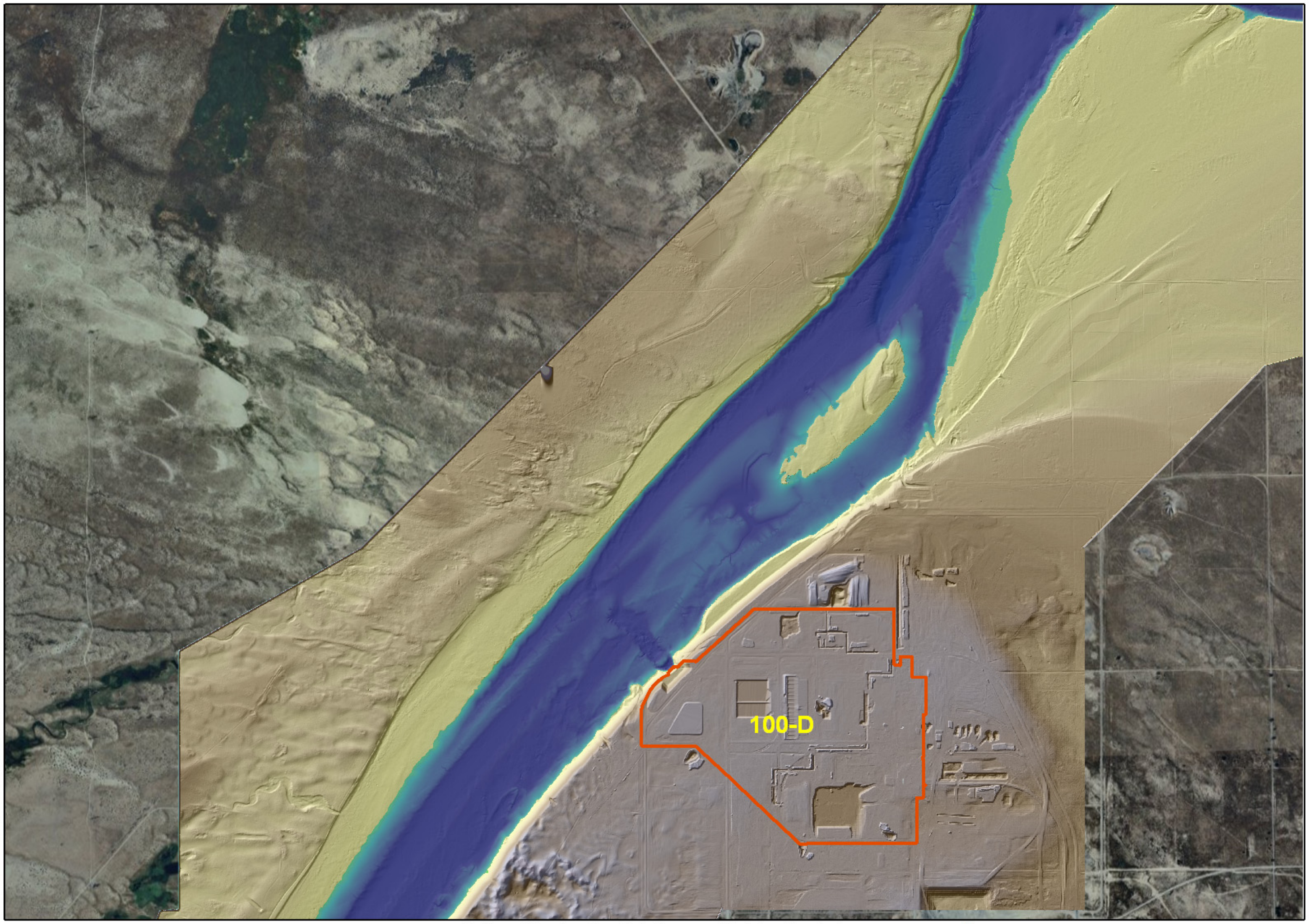

Hanford Reach Bathymetry
Map 7
Map Produced: September 2010

Bathymetric Elevation (m)
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Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest National Laboratory

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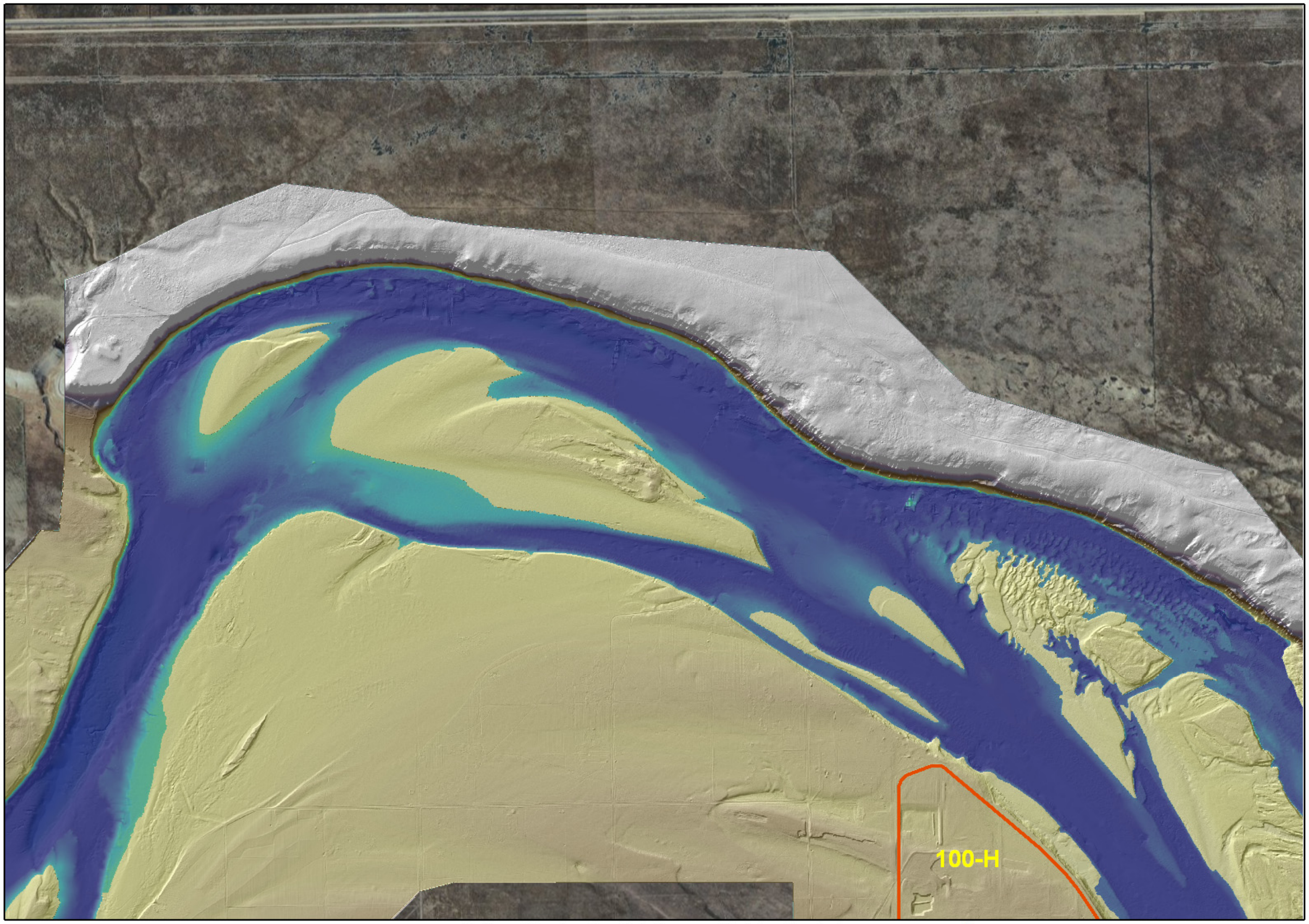

Hanford Reach Bathymetry

Map 8

Map Produced: September 2010

Bathymetric Elevation (m)
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Topographic Elevation (m)
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Pacific Northwest National Laboratory

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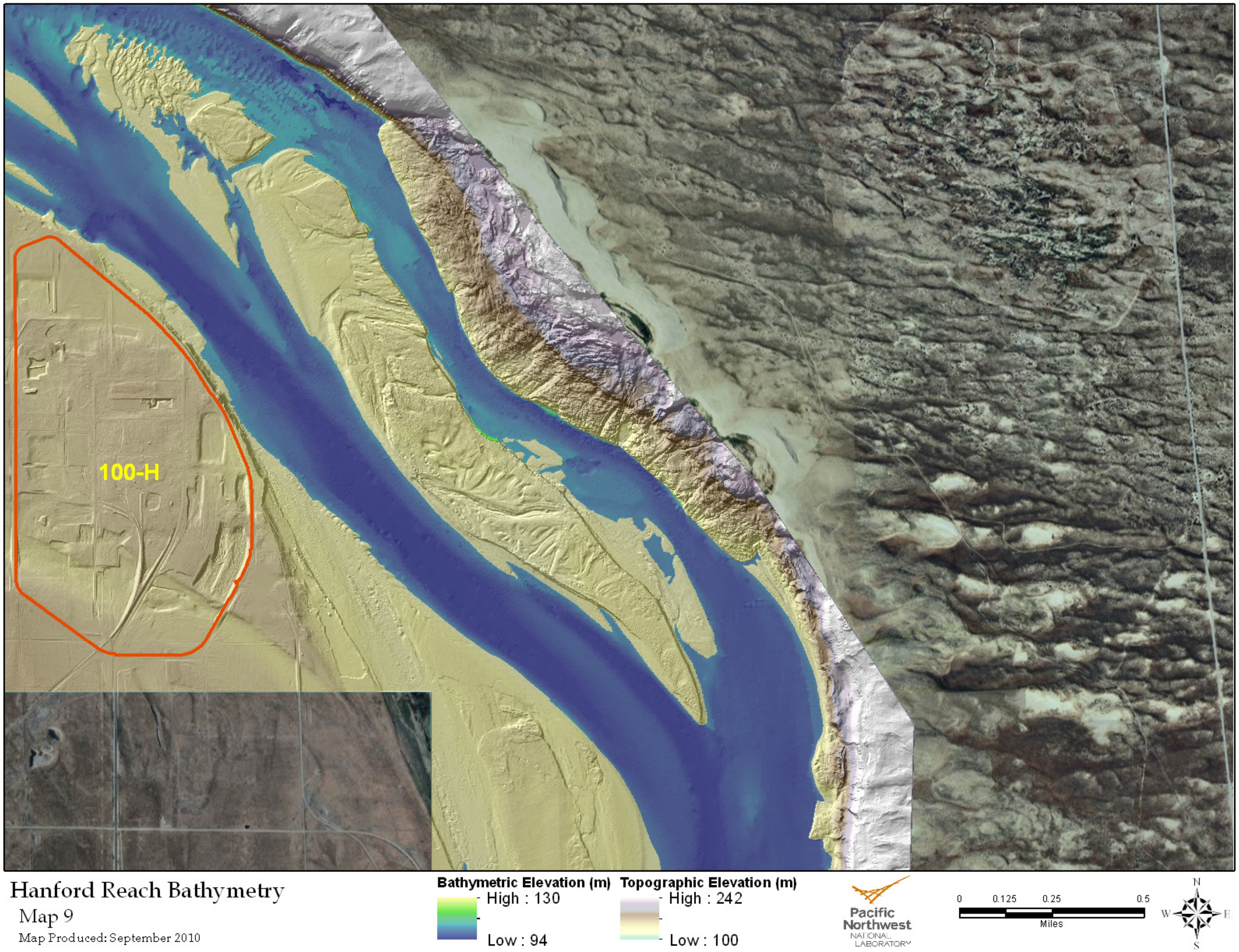
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Hanford Reach Bathymetry
Map 9
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Topographic Elevation (m)
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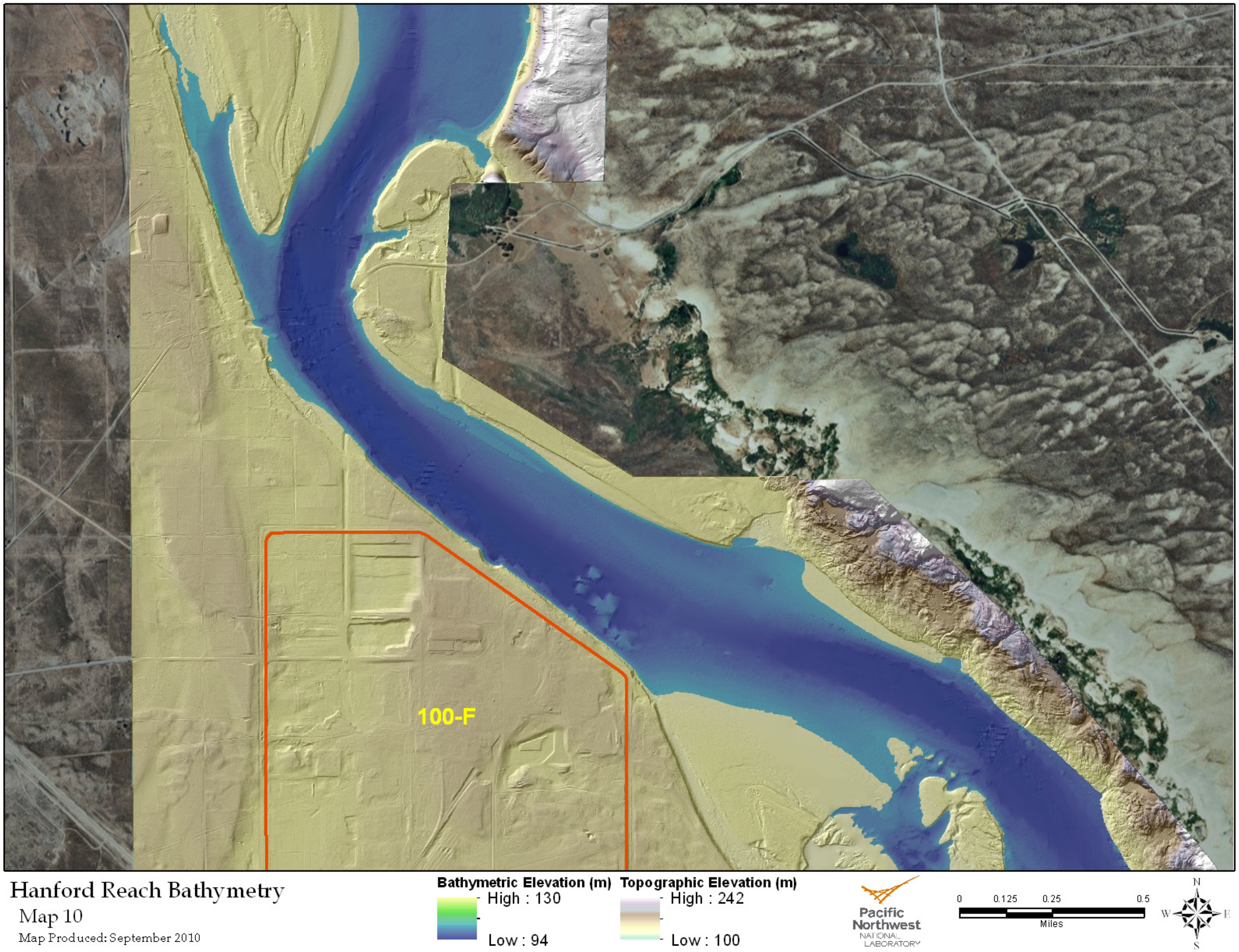
100-F
Hanford Reach Bathymetry
Map 10
Map Produced: September 2010
Bathymetric Elevation (m)
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Low : 94
Topographic Elevation (m)
High : 242
Low : 100
Pacific Northwest National Laboratory
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Hanford Reach Bathymetry

Map 11

Map Produced: September 2010

Bathymetric Elevation (m)
High : 130
Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest National Laboratory

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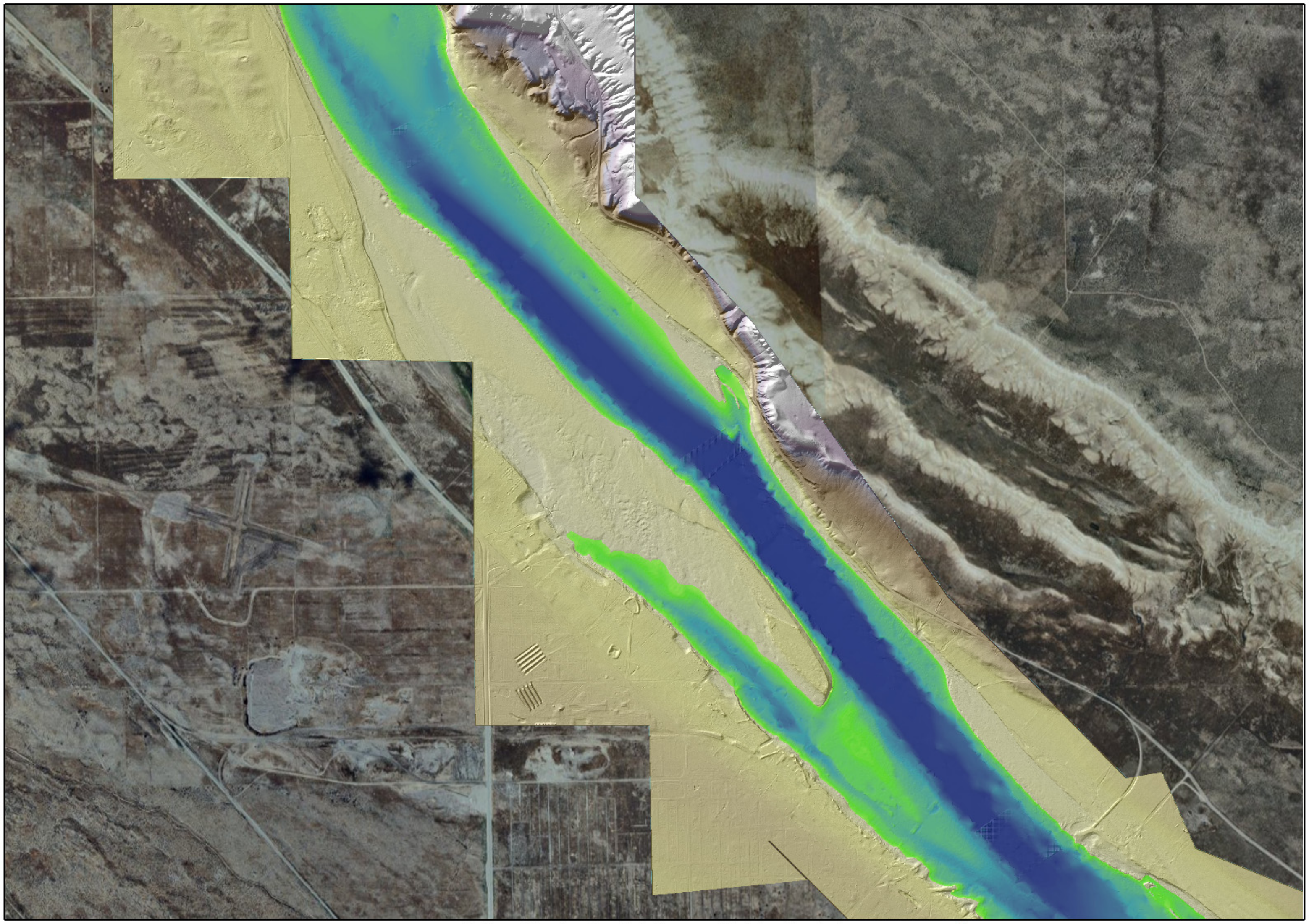
N W E S



Hanford Reach Bathymetry

Map 12

Map Produced: September 2010

Bathymetric Elevation (m)

High : 115

Low : 94

Topographic Elevation (m)

High : 242

Low : 100

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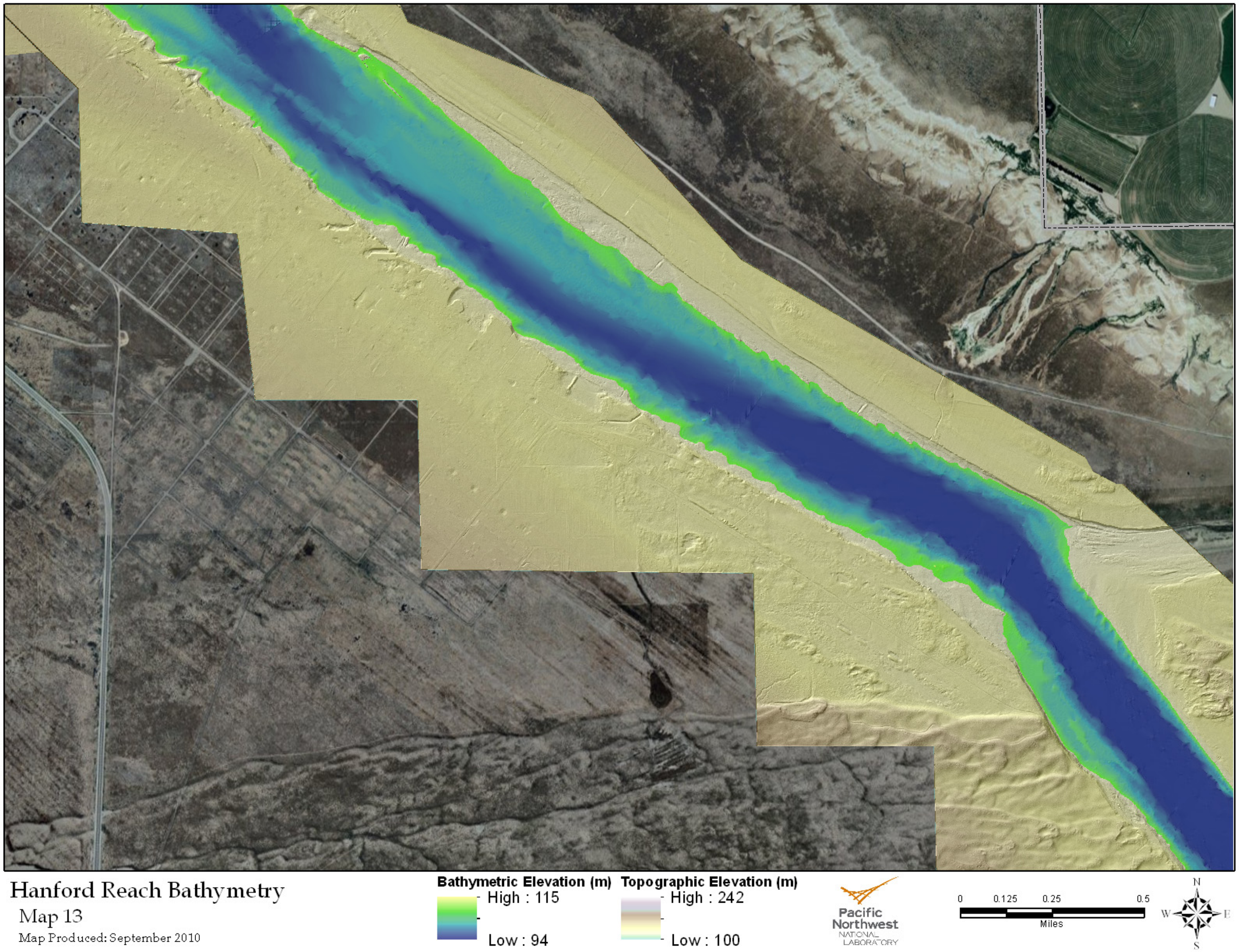
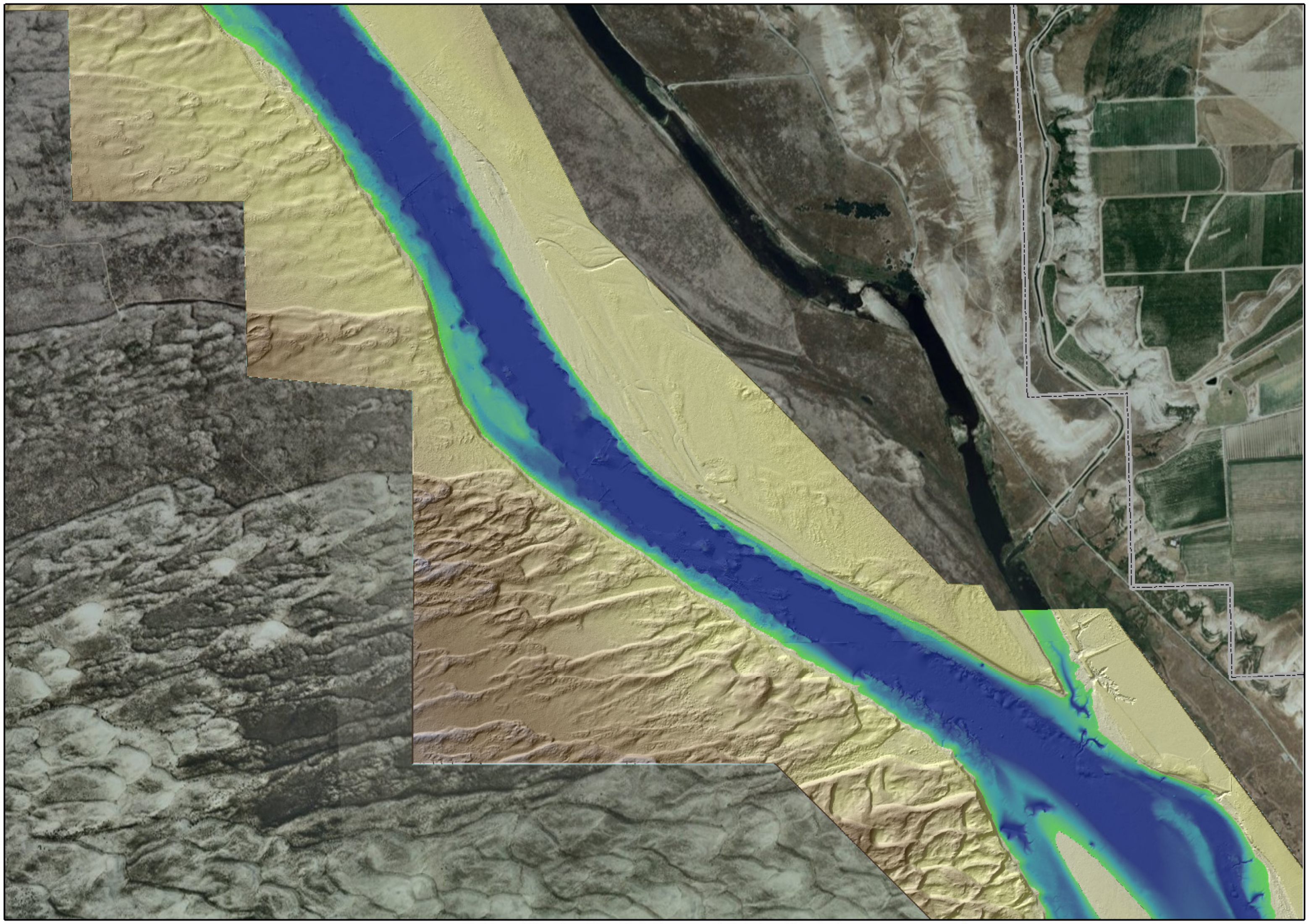


Hanford Reach Bathymetry

Map 13

Map Produced: September 2010



Hanford Reach Bathymetry

Map 14

Map Produced: September 2010

Bathymetric Elevation (m)
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Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

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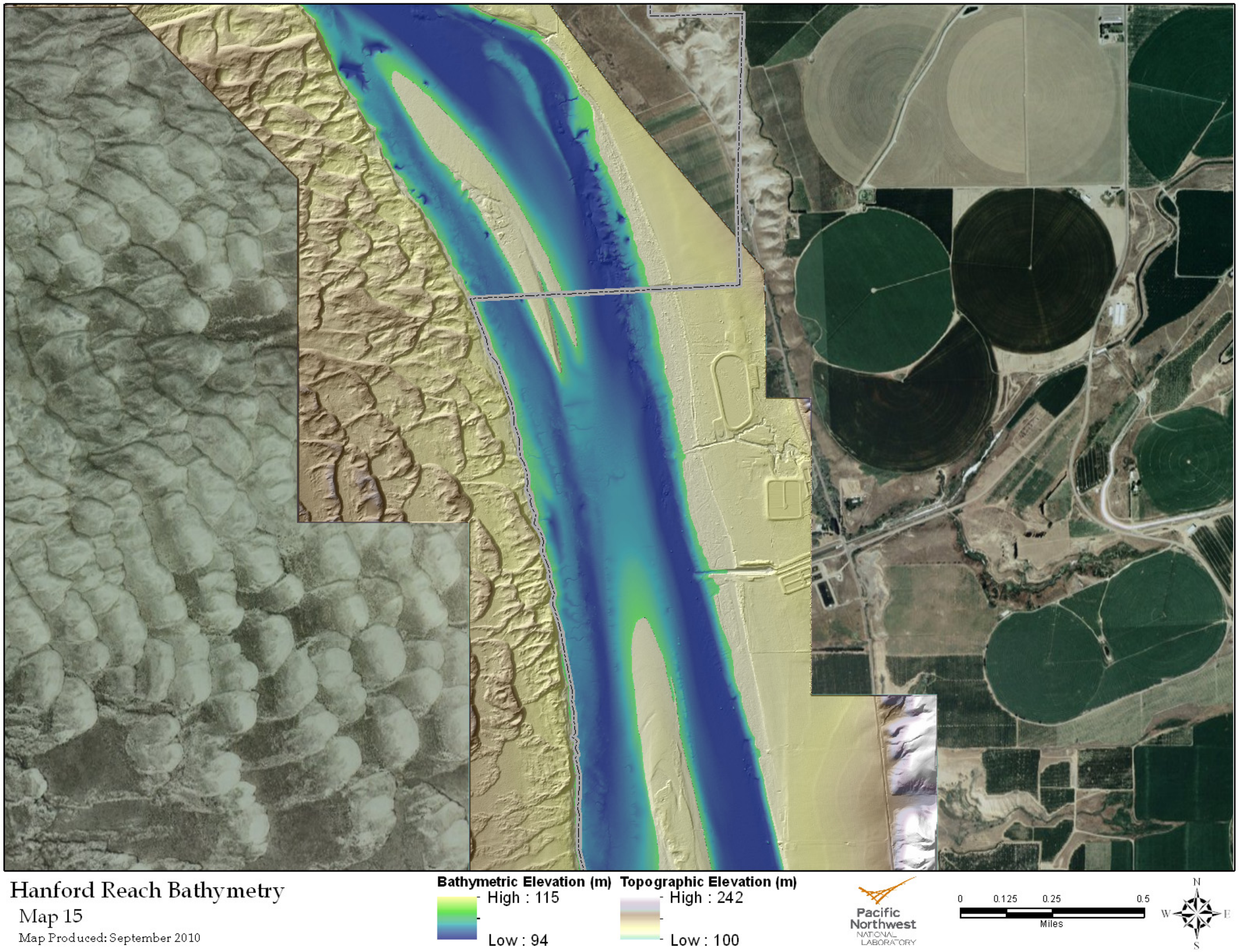
Hanford Reach Bathymetry
Map 15
Map Produced: September 2010
Bathymetric Elevation (m)
High : 115
Low : 94
Topographic Elevation (m)
High : 242
Low : 100
Pacific Northwest
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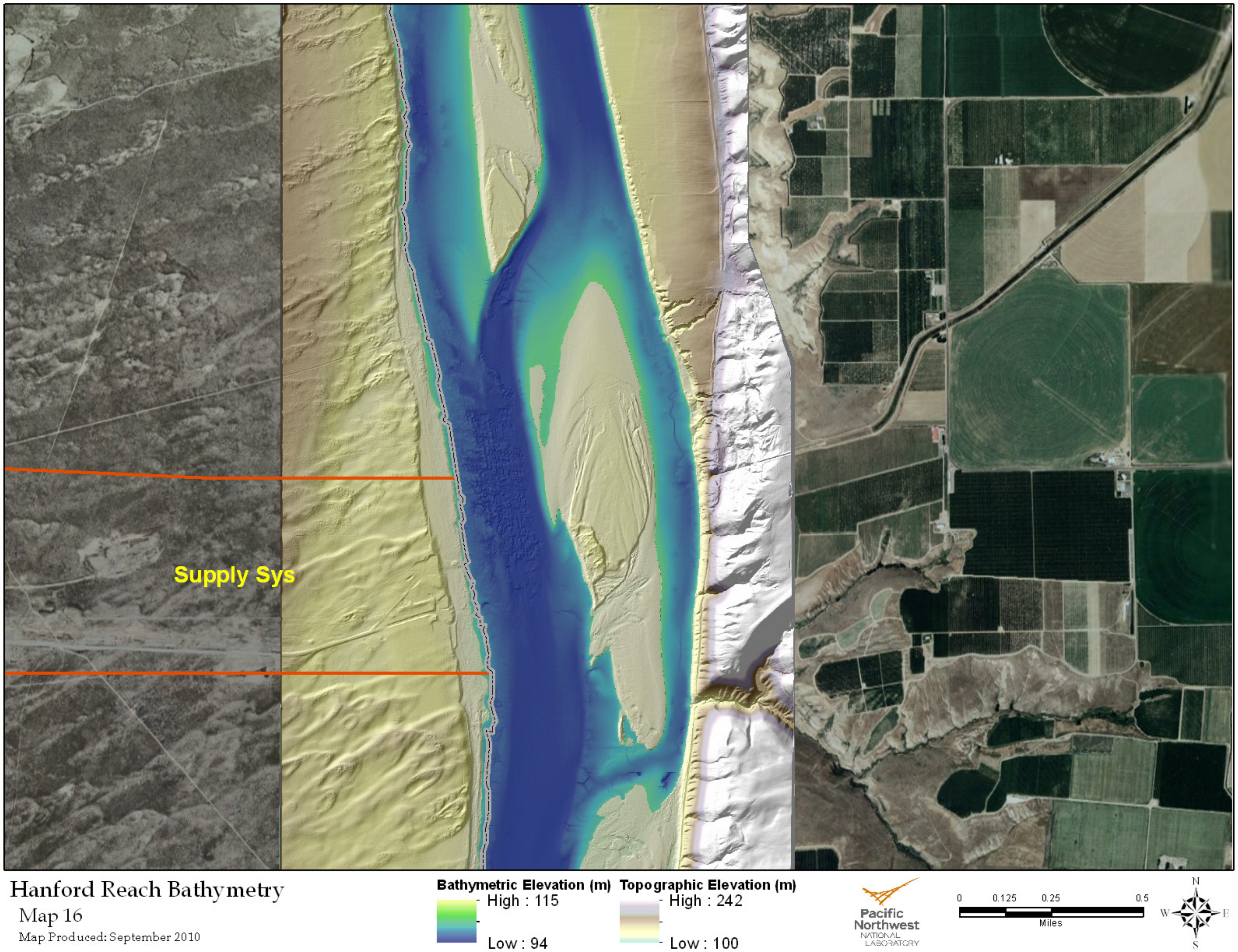
S


Supply Sys
Hanford Reach Bathymetry
Map 16
Map Produced: September 2010
Bathymetric Elevation (m)
High : 115
Low : 94
Topographic Elevation (m)
High : 242
Low : 100
Pacific Northwest
NATIONAL LABORATORY
0
0.125
0.25
0.5
Miles
N
W
E
S

Hanford Reach Bathymetry
Map 17
Map Produced: September 2010

Hanford Reach Bathymetry

Map 18

Map Produced: September 2010

Bathymetric Elevation (m)
High : 115
Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

0 0.125 0.25 0.5
Miles

N
W E
S

Hanford Reach Bathymetry

Map 19

Map Produced: September 2010

Bathymetric Elevation (m)
High : 115
Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

0 0.125 0.25 0.5
Miles

N W E S

Hanford Reach Bathymetry

Map 20

Map Produced: September 2010

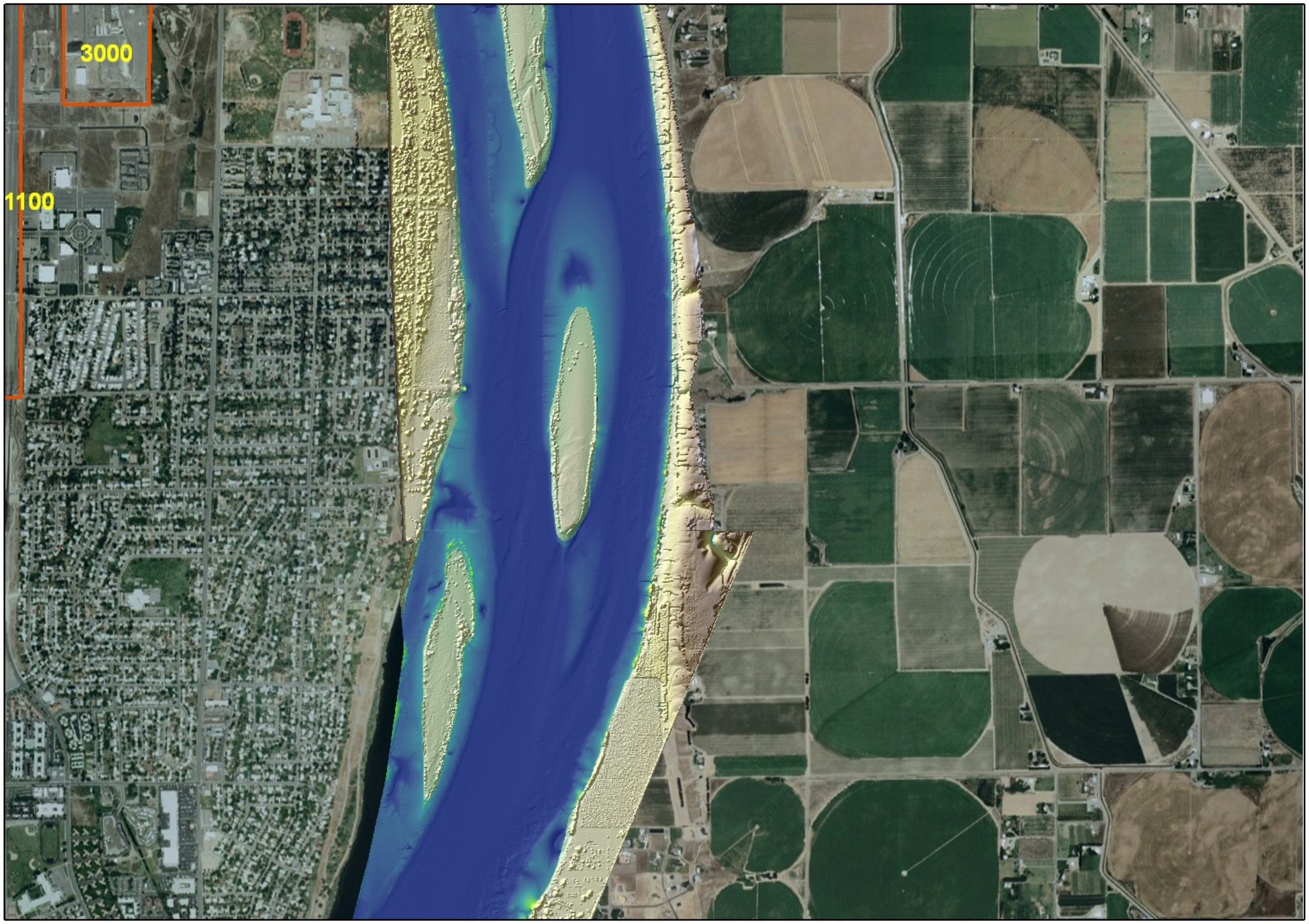
Bathymetric Elevation (m)
High : 115
Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

0 0.125 0.25 0.5
Miles

N W E S



Hanford Reach Bathymetry

Map 21

Map Produced: September 2010

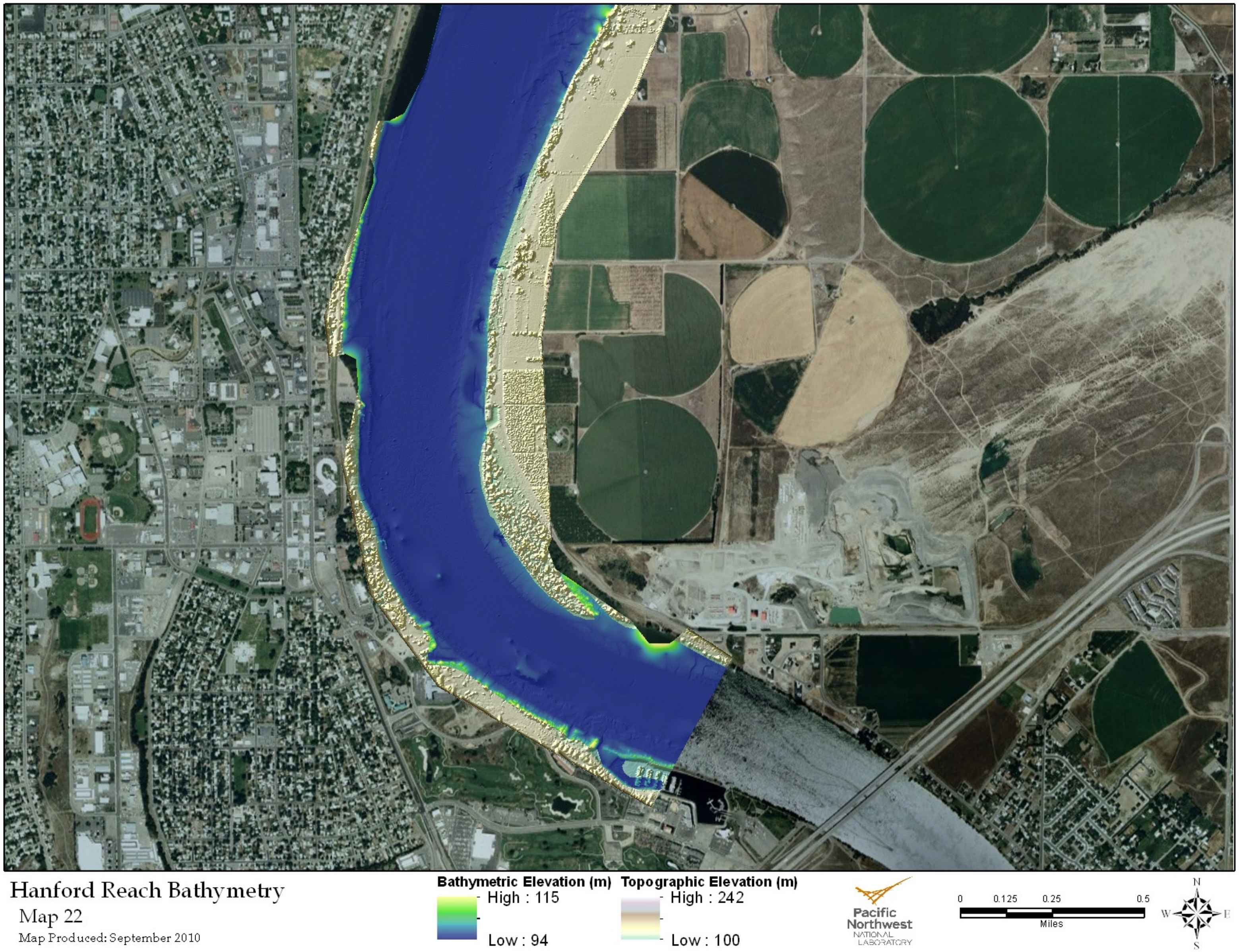
Bathymetric Elevation (m)
High : 115
Low : 94

Topographic Elevation (m)
High : 242
Low : 100

Pacific Northwest NATIONAL LABORATORY

0 0.125 0.25 0.5
Miles

N S W E


Hanford Reach Bathymetry
Map 22
Map Produced: September 2010
Bathymetric Elevation (m)
High : 115
Low : 94
Topographic Elevation (m)
High : 242
Low : 100
Pacific Northwest
NATIONAL LABORATORY
0
0.125
0.25
0.5
Miles
N
W
E
S

Appendix B

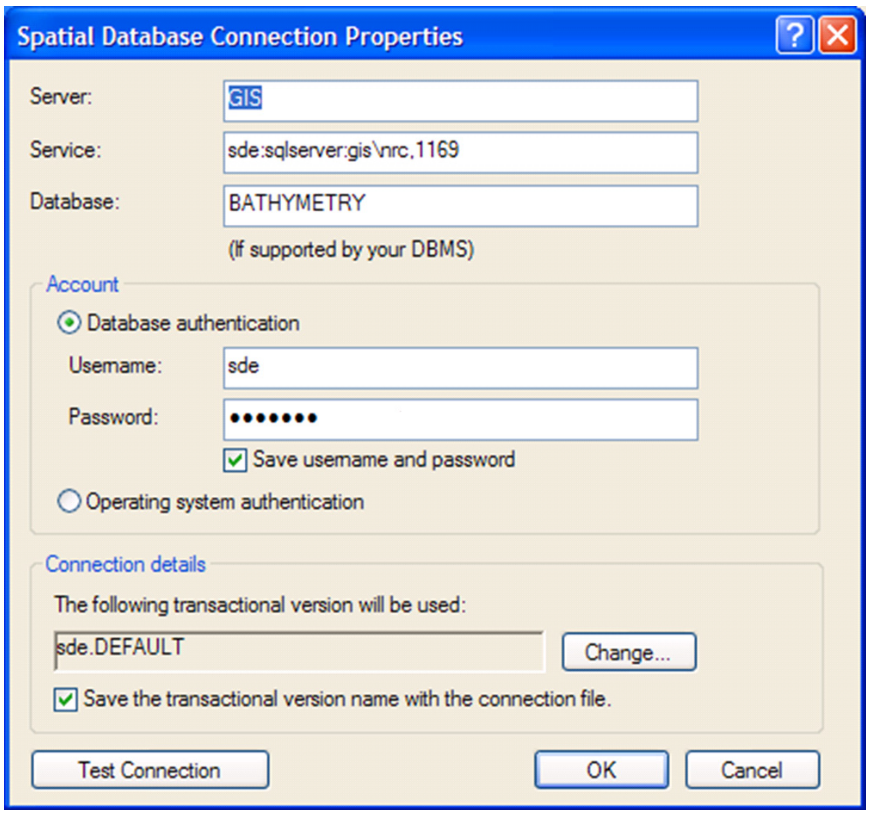
Remote Connection

Appendix B

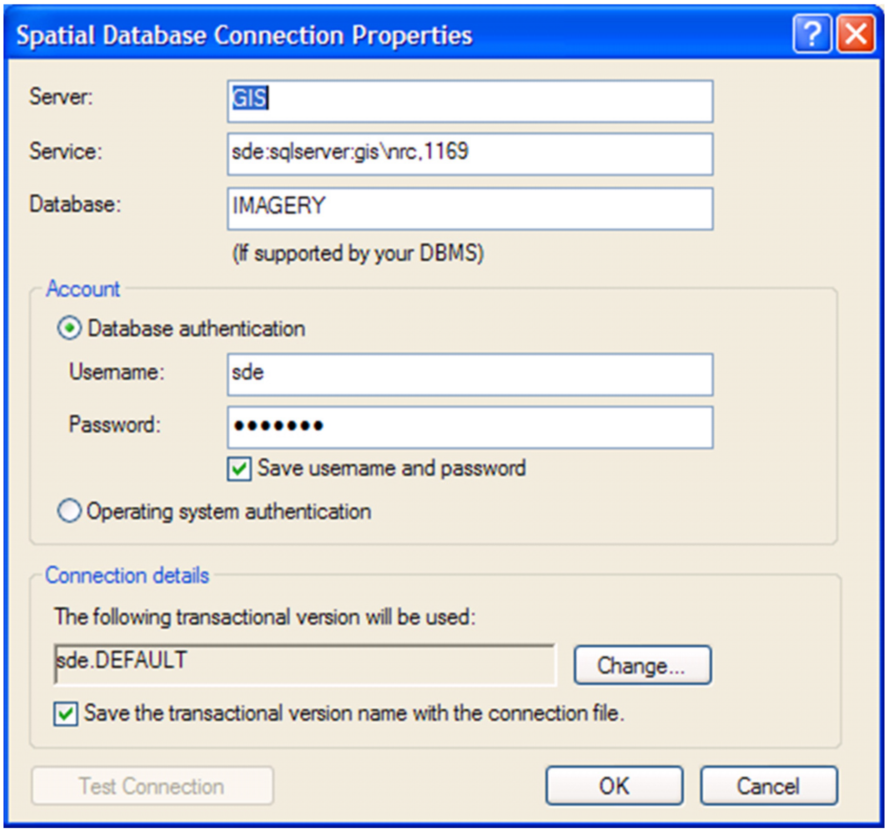
Remote Connection

PNNL ESRI ArcSDE Geodatabases
ArcCatalog Database Connection Properties for ArcGIS Desktop v9.3x or v10
As of 8/28/2010

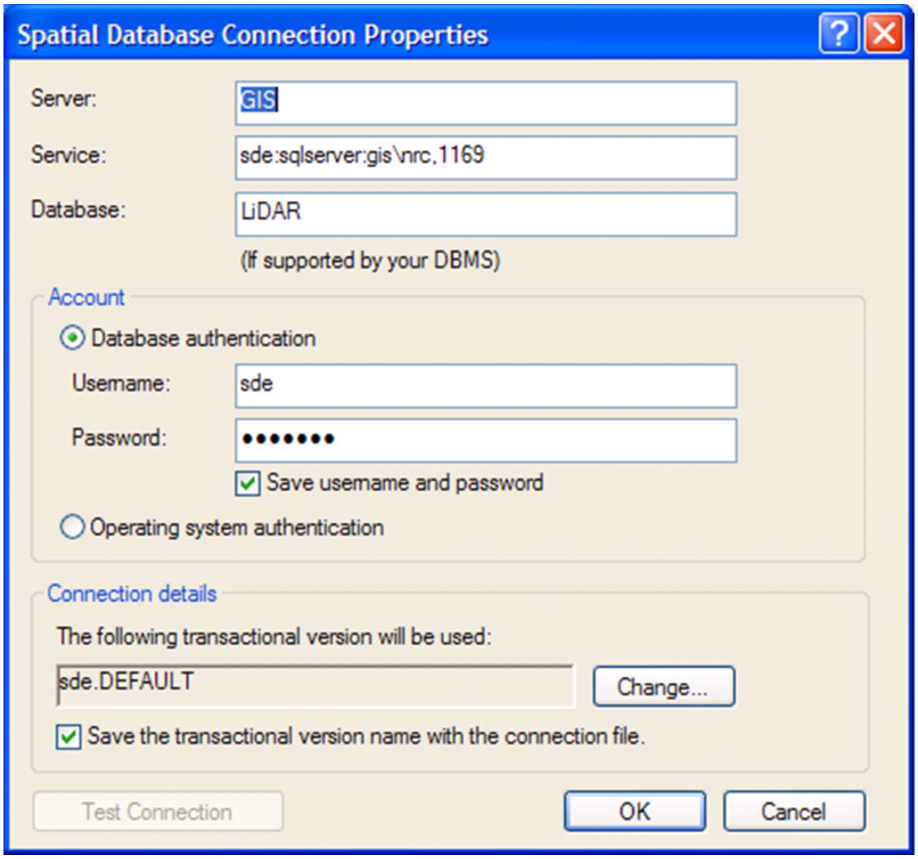
GISX.pnl.gov (Bathymetry)
- 2010 Bathymetry Datasets



GISX.pnl.gov (Imagery)
- Hanford 2008 Hi-res Imagery (1ft. , 0.5 RGB, 0.5 CIR)
- 2006 -Benton County NAIP (1m)



GISX.pnl.gov (LiDAR)
- Hanford 2008 Terrestrial LiDAR Datasets



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