ERDC/CRREL TN-06-3

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Delineating and Evaluating Vegetation Conditions of Vernal Pools Using Spaceborne and Airborne Remote Sensing Techniques, Beale Air Force Base, CA

Robert W. Lichvar, David C. Finnegan, Stephen Newman, and Walter Ochs

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Prepared for U.S. Air Force, Beale Air Force Base, CA

Abstract: Remote sensing techniques were employed to identify aquatic resources, including vernal pools and riparian areas, at Beale Air Force Base (AFB) in September 2005. Aquatic resources previously identified at Beale AFB were delineated in the field and precisely located with a global position system (GPS). Though precise, these GPS maps were not comprehensive enough to fully understand the distribution and character of the aquatic system. Using those field results, we developed techniques to identify these and similar locations using digitally derived spectral signatures from IKONOS high-resolution multispectral imagery. To refine the delineation results obtained from the multispectral imagery, high-resolution topographic data were acquired over the study area using NASA's Airborne Topographic Mapper (ATM) waveform LiDAR. Using the post-processed digital elevation models (DEM) and a series of statistical approaches, we eliminated many false positive identifications and developed a comprehensive Geographic Information System (GIS) based set of maps for three distinct groupings of vernal pools. These groupings were rated from most similar to previously field-identified vernal pools, to areas with moderate probability to be similar and least similar but still considered areas of interest. The original field mapping results located 244.0 ha of vernal pools and swales; our remote sensing efforts found 411.5 ha. This represents a 169% increase in potential vernal pool locations over the previous estimate.

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Preface

This report was prepared by Robert W. Lichvar, David C. Finnegan, Stephen Newman, and Walter Ochs, all of the Remote Sensing/GIS and Water Resources Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, NH. Funding for this study was provided by Beale Air Force Base, CA.

The report was prepared under the general supervision of Timothy Pangburn, Chief, Remote Sensing/GIS and Water Resources Branch; Dr. Lance Hansen, Deputy Director; and James L. Wuebben, Acting Director, CRREL.

The Commander and Executive Director of ERDC is COL Richard B. Jenkins. The Director is Dr. James R. Houston.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
hectares	1.0 E+04	square meters

1 Introduction

The U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (ERDC/CRREL) and ERDC Environmental Laboratory (EL) have designed supportive studies to define and evaluate the aquatic and hydrologic resources for approximately 23,000 acres at Beale Air Force Base (AFB), CA, in support of a Special Area Management Plan (SAMP) under the U.S. Army Corps wetlands program. Beale AFB contains numerous large complexes of vernal pool communities along its western margin, while the eastern margin exhibits several riparian corridors with numerous stands of mature vegetation (Fig. 1). Several large areas of these aquatic resources are located in areas targeted for future development. To coordinate all section 404 permits and mitigation actions as defined by the Clean Water Act and the "Waters of the Unites States" (WoUS), a large-scale understanding of the aquatic and hydrologic systems is necessary to avoid dissection and ecological isolation of resources, which may result in lower overall quality. This report describes the first phase of a study that uses a fusion of remote sensing techniques and analysis to quantify and delineate the aquatic and hydrologic resources within known and unknown vernal pool complexes and riparian corridors. The results will be used to increase accuracy of wetland delineations in the field and for modeling the wetland functions at the landscape scale.

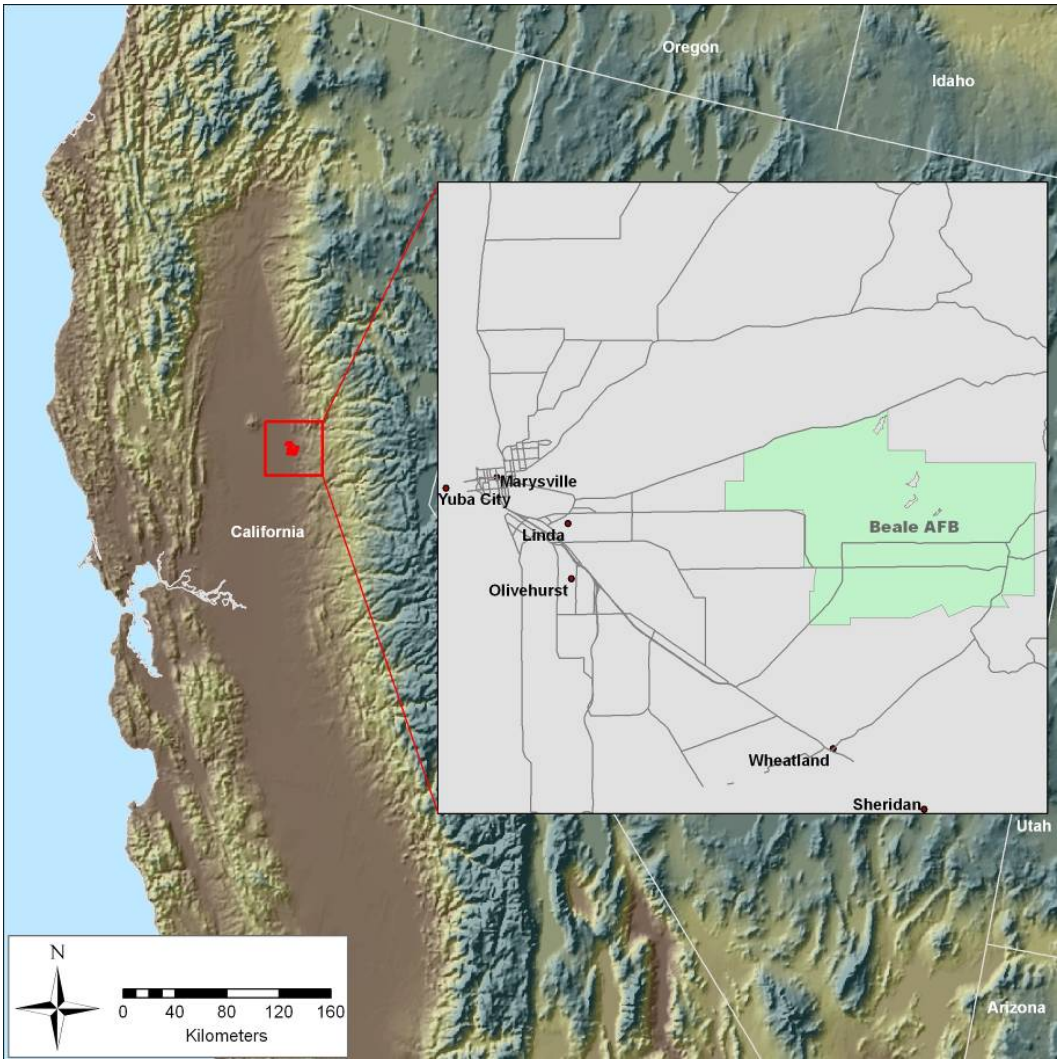


Figure 1. Location of Beale AFB in north-central California. The inset shows the Beale AFB boundary and the proximity to Yuba City.

2 APPROACH

Our approach to this study uses a fusion of high-resolution airborne and spaceborne remote sensing data acquired at similar scales alongside field-derived vernal pool mapping results to determine the precise location, depth, and quality of known and unknown aquatic and hydrologic resources. These include supervised image classification techniques using IKONOS 1-m panchromatic and 4-m multispectral satellite imagery as a means of delineating the boundaries of vernal pool complexes that actively pond and convey waters. These pool complexes can then be compared with GPS pool complex maps provided in geographic information system (GIS) format by the Beale AFB Environmental Program. Remote sensing efforts such as these are commonly accepted and well documented in the scientific literature as valid techniques for delineating aquatic and hydrologic resources in numerous environments (Lunetta et al. 1999, Shepherd et al. 2000, Chopra et al. 2001, Goetz et al. 2003).

As an additional step towards a refined delineation map and validation of classification-derived maps from the multispectral imagery, airborne LiDAR (Light Detection and Ranging), a source of high-resolution topography, was acquired using NASA's Airborne Topographic Mapper (ATM-IV) over the entire Beale AFB installation. The high-resolution (2-m) digital elevation model (DEM) provided by the LiDAR is a key data set that can be used as a highly precise base for all analysis, mapping, and delineation efforts. Utilizing these data in a fine-scale topographic analysis, we derived large-scale depth and delineation maps of individual vernal pools and hydrologic complexes. These data were then used individually or in combination with multispectral and GIS mapping results to provide concise maps of all aquatic systems. These data and techniques also lend themselves to statistically understanding the distribution of resources.

3 METHODS AND DATA

Multispectral Imagery

Two IKONOS high-resolution multispectral images (12 × 12 km) were acquired to obtain complete coverage of Beale AFB. This commercial satellite, operated by Space Imaging Inc. (Thornton, Colorado), simultaneously acquires four-band multispectral imagery with 11-bit radiometric resolution at 4-m (multispectral) and 1-m (panchromatic, black and white) spatial resolutions. The multispectral images consist of four bands in the blue (444–0.516 µm), green (0.506–0.595 µm), red (0.632–0.697 µm), and near-infrared (0.757–0.853 µm) wavelength regions, all of which were provided in a bundled product to CRREL. The image acquisition dates used in this study were January 5 and January 27, 2001.

The following processing occurred to integrate the multispectral image data with existing GIS and LiDAR data structures using ERDAS Imagine 8.7 software (ERDAS-Imagine 2005):

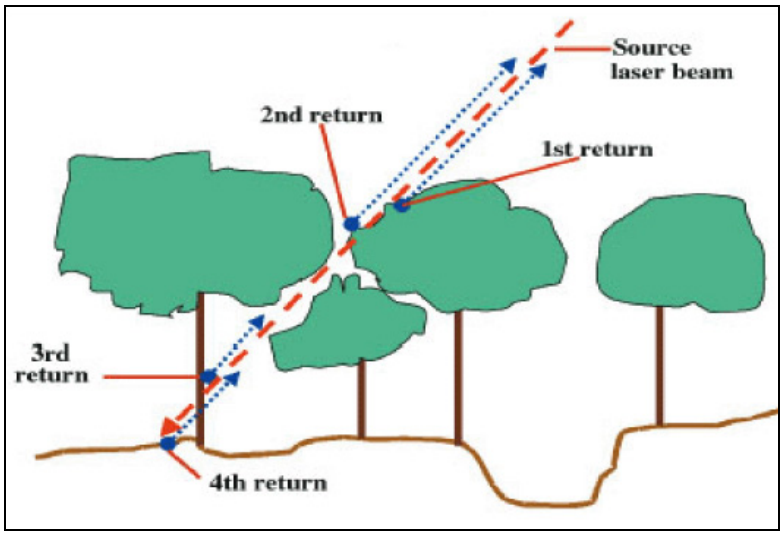
- Reprojection of both image dates to UTM.
- Pan-sharpening: Each image scene was pan-sharpened by fusing the 4-m multispectral imagery (MSI) with the 1-m panchromatic imagery using a Brovey transform. This produced radiometrically calibrated 1-m multispectral images.
- Image normalization: The pan-sharpened images were normalized using an empirical line calibration process. This process converts the band-wise Digital Number (DN) values of one image to the calibration units of the other image. Band-wise correlation coefficients were greater than 0.975, ensuring consistency in the radiometric calibration between the two images. Accurate image normalization is critical when mosaicking multi-temporal imagery for supervised classification processes.
- Co-registration and mosaicking of the multispectral imagery into a seamless four-band, 1-m image. This mosaic image was used for all subsequent image analysis and map generation.

Airborne LiDAR

NASA's Airborne Topographic Mapper LiDAR instrument (ATM-IV) is an aircraft-based scanning laser altimeter flown onboard a twin-engine light aircraft based at NASA's Wallops Flight Facility in Virginia. The ATM-IV sensor operates at 2,000–10,000 pulses per second at a frequency-doubled wavelength of 532 nm in the blue-green spectral region. For each laser pulse emitted, a returned spatial vector from the platform to the point of reflection is established, providing an extremely precise XYZ coordinate of the laser footprint. Using a conical scanning mirror rotated at 10–20 Hz at an off-nadir angle of 10°, the beam of the ATM is directed along an elliptical scanning pattern beneath the aircraft. Swath widths directly correspond to flight altitude and rotation rates of the scanning mirror and are normally on the order of 650 m. The ATM-IV is unique in that it utilizes a waveform digitizer. The waveform digitizer allows for simultaneous acquisition of multiple elevation points for each laser measurement (>160 per laser measurement), providing the capability of precisely reconstructing the vegetation, vegetation canopy, and bare earth, the latter of which was used in this study (Fig. 2).

The LiDAR survey over Beale AFB occurred on September 7 and 8, 2005, and utilized a Twin Otter International twin-engine aircraft equipped with the ATM-IV instrument, a laser Ring-Gyro Inertial Navigation Unit (INU), two survey-grade GPS receivers, and a waveform digitizer flown at an altitude of approximately 1000 m above ground level. The aircraft's position was determined by combining the aircraft's GPS data with signals collected concurrently at an established nearby GPS base station at the Yuba City airport using differential kinematic GPS techniques. The INU provides the aircraft's pitch, roll, and heading, which are embedded in the ATM telemetry through post-flight processing. By integrating individual measurements from the laser altimeter and kinematic GPS receivers, the ATM achieves reproducible measurements of vertical surface topography to approximately 5 cm (Krabill et al. 2002). The horizontal spacing depends on the aircraft's altitude and speed but generally ranged from 25 to 75 cm for this study.

Post-flight processing, calibration, and data quality and assurance checking were performed by the NASA ATM group. ATM data acquired over Beale AFB entail approximately 90 million individual latitude, longitude, and elevation measurements of surface topography. Once the



a. Simplified diagram showing multiple laser measurements acquired for each laser point.

b. ATM-IV instrument mounted within the Twin Otter aircraft.

c. Established differential GPS base station used for precise trajectory information during LiDAR surveys.

Figure 2. LiDAR survey equipment.

ATM data were released to CRREL on DVD, the following post-processing was done to integrate the data with existing GIS data structures using custom software interfaces written with IDL (Research Systems Inc. 2005):

- Projecting all WGS84 horizontal data to UTM NAD83 format and converting vertical elevation data from ITRF00 to the NAVD88 datum.
- Filtering data for false triggers, atmospheric effects, and erroneous data.
- Examining data concentrations for sufficient point densities before gridding to DEMs.
- Generating a 2-m seamless, installation-wide DEM.

- Gridding all data (bare earth) to higher-resolution 4- × 4-km, 1-m DEMs.
- Generating ESRI/ARCINFO raster DEM formats.

Figure 3 shows the resulting 2-m DEM.

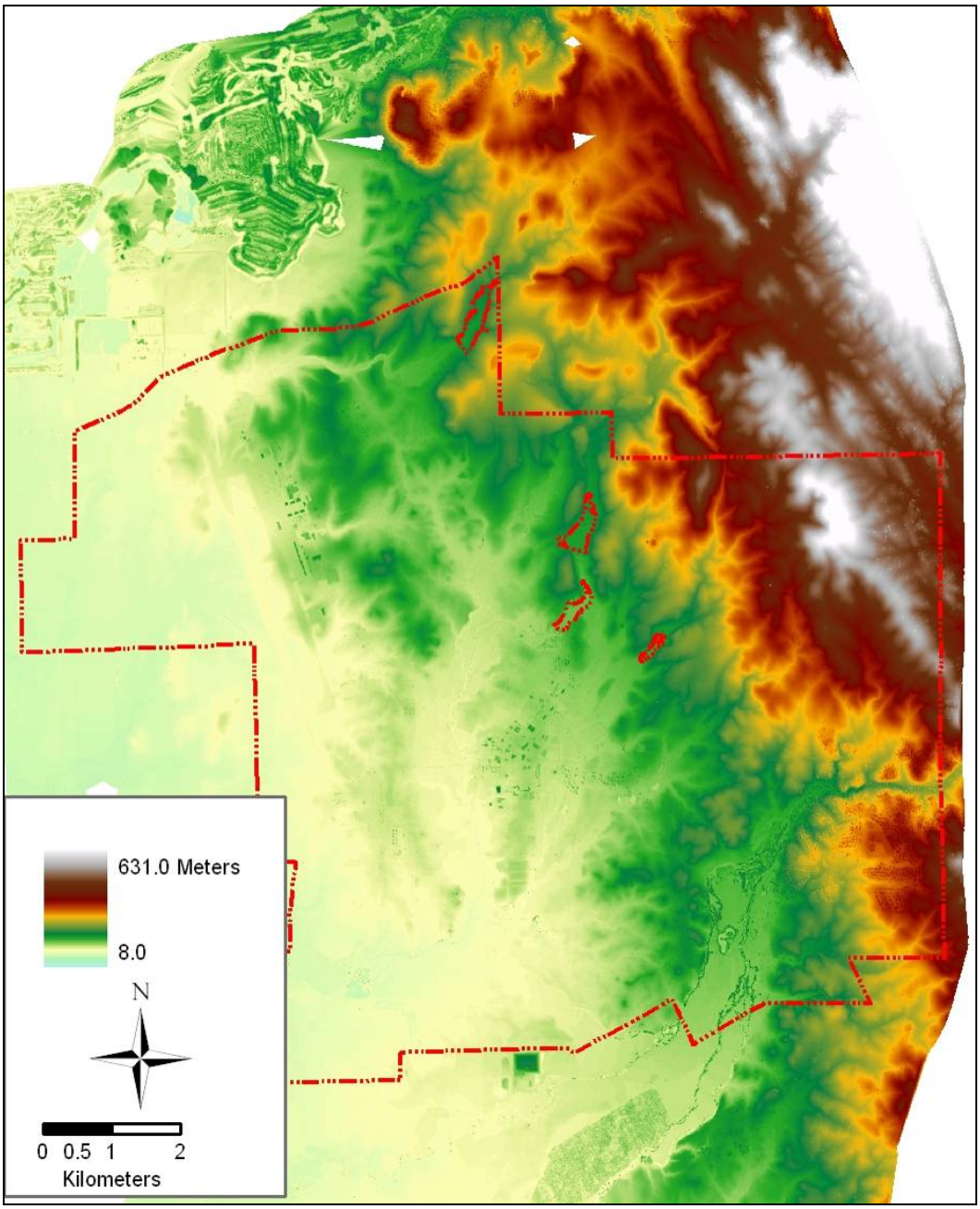


Figure 3. Large-scale, color-coded 2-m DEM of Beale AFB (red outline) derived from NASA ATM-IV LiDAR data acquired on September 7 and 8, 2005.

4 ANALYSIS

Multispectral Imagery

An analysis of the 31-year average precipitation record (1959–1990) for Marysville and Englebright Dam compared to the 12-month record surrounding the image acquisition dates clearly shows that precipitation at Beale AFB in January 2001 was above the historical average (Fig. 4). The increased precipitation rates around the image acquisition dates resulted in water levels within the aquatic resources would be at a suspected annual maximum. This high water physical expression in the imagery was critical in locating vernal pools, their complexes, and other aquatic resources.

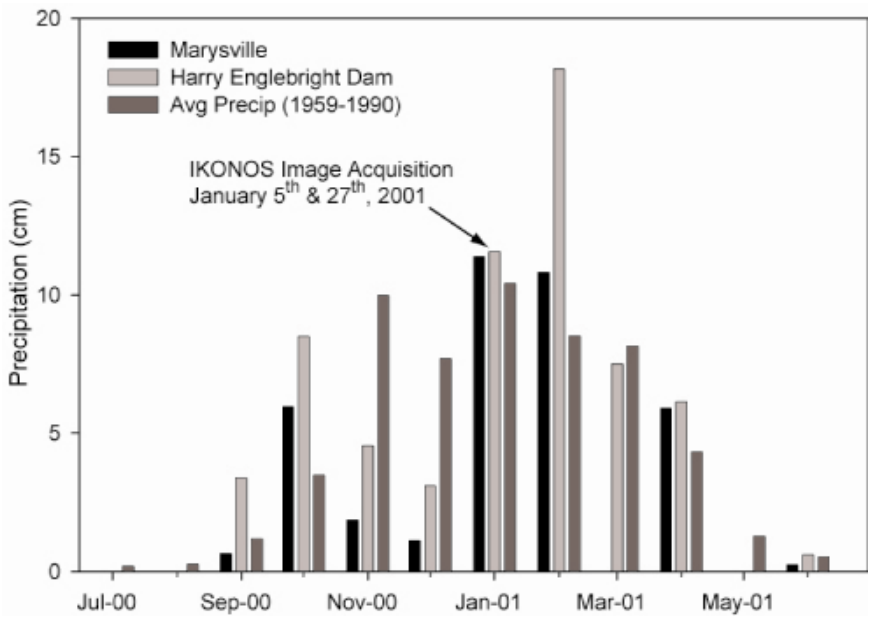


Figure 4. 2000–2001 Beale AFB precipitation data vs. 31-year average. The 31-year average was derived from Marysville and Englebright Dam meteorological station data.

A hybrid classification technique was used during the multispectral image classification of the IKONOS scenes (Fig. 5). This technique employed both unsupervised classification (ISODATA) and supervised classification (maximum likelihood) in a sequential processing chain to isolate, characterize, and map the vernal pool complexes. First, ISODATA clustering was used to segment the image into three primary data sets: water features, bare soil features, and vegetated features. Fifty clusters were classified within each of the three segments. The spectral signatures

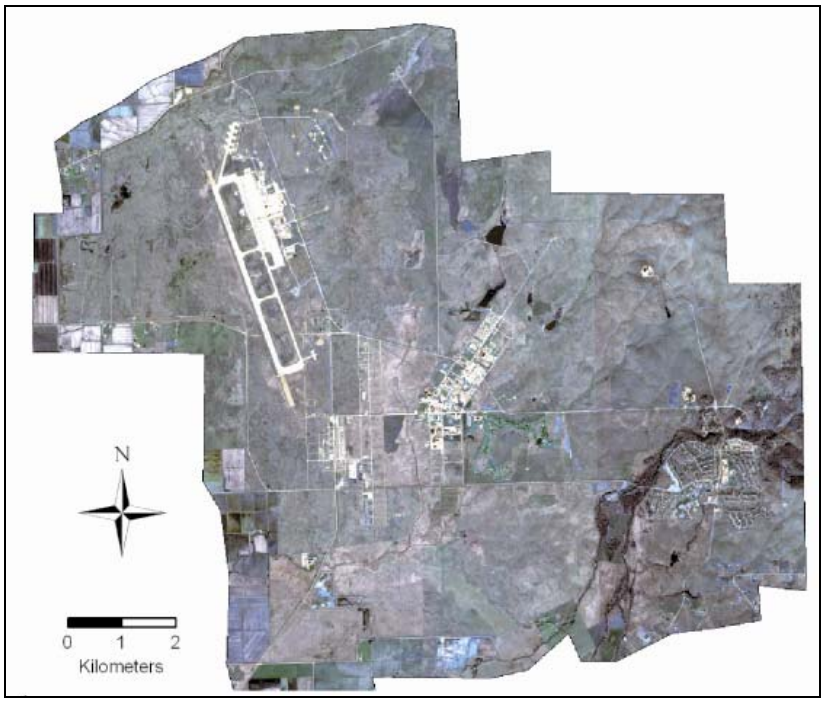


Figure 5. IKONOS color composite image mosaic of Beale AFB (January 5 and 27, 2001).

were plotted and, along with visual interpretation of the IKONOS scene, were used to assign a descriptive class name to each cluster. Clusters that were identified as vernal pools were retained for further analysis, while the remaining portion of the image was removed from analysis. Common false positives included building shadows, tree shadows, topographic shadowing, and roadways. A second ISODATA analysis or cluster-busting technique was used on the remaining clusters to segment the classes further and isolate only vernal pools. Similar clusters were aggregated within each segment, and spectral signatures of three primary vernal pool types were developed.

The refined spectral signatures were then used in a supervised classification algorithm. These signatures represented a range of vernal pools, hydrology, and riparian resources within Beale AFB. Two primary analyses were used to assess the spectral signatures. First, the field-delineated vernal pool and swale polygons provided by the Beale Environmental Program were used to identify the four major aquatic resource categories across Beale AFB: vernal pools, seasonal swales, disturbed seasonal, and other seasonal. The polygons were used to examine the spectral variability in the IKONOS imagery between each of

these categories. This analysis identified the dynamic range of spectral variability and helped identify the appropriate number of signatures needed to map all aquatic resources on Beale AFB.

Second, the signatures were evaluated for separability in the IKONOS imagery. The four-dimensional mean vectors and covariance matrices were computed to estimate the magnitude of pair-wise difference for each of the 20 spectral signatures. The results of the signature separability tests highlighted those signatures that best delineated the variation of vernal pool types across the base. It also identified those signatures that, while supporting unique vernal pool complexes, were not distinct in their spectral properties. This information was used to refine the signature sets to three primary vernal pool types (Fig. 6) and detect and map the water resources across Beale AFB. A significant feature of these signatures is their varying response in the near-infrared (band 4). Each signature has similar characteristics in bands 1–3 (the visible bands), whereas the differences in these bands are primarily amplitude shifts with very little difference in slope. Band 4, which is a near-infrared band, shows widely varying shape and amplitude shifts. These differences are primarily caused by an increasing component of vegetation in the signatures from vernal pool Type 1 to Type 3. The observed characteristics of each vernal pool type are listed below:

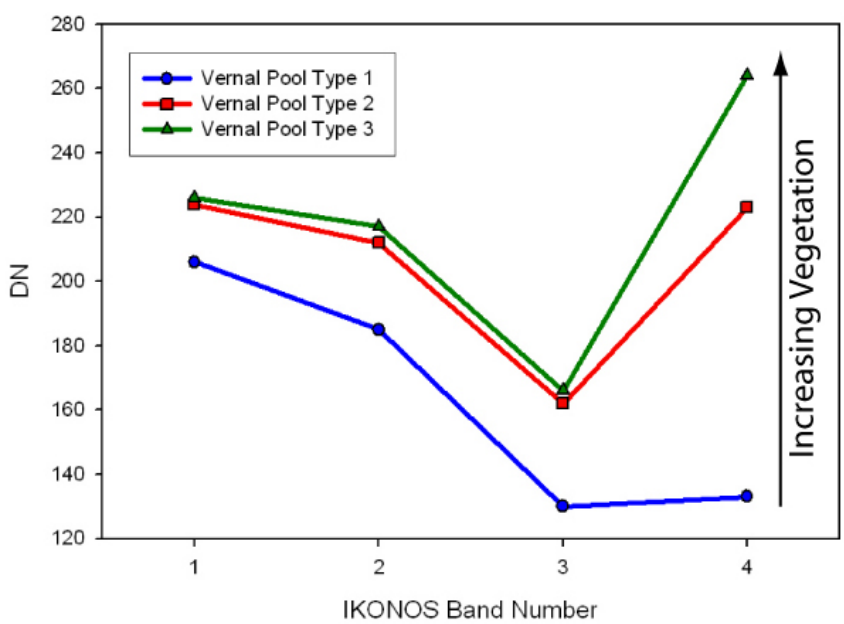


Figure 6. Spectral signatures derived from the IKONOS multispectral imagery and used in the final supervised classification. Each signature class represents a vernal pool probability rating from high (1) to low (3).

- Type 1: Longest duration of ponding. This corresponds with deep pools with little to no vegetative cover at the time of image acquisition.
- Type 2: Intermediate-duration ponding and saturated soils. The majority includes saturated soils associated with vernal pool margins, temporary flowing water in swales, and hillside seeps. Shallow pools with short-duration ponding and wet soils are also included in this category. The vegetative cover is low to moderate.
- Type 3: Short-duration moist soils. This may include swales and seeps. There is a significant vegetative component in this vernal pool category.

LiDAR

Numerous steps were taken to analyze the ATM LiDAR-derived topography for depression features that might be considered active or potential aquatic or hydrologic resources. Using a 2-m installation-wide DEM derived from the LiDAR data, a 50-m boxcar moving-window-average filter was used to create an averaged (smoothed) DEM. This DEM was then subtracted from the original DEM to determine the change in elevation for each grid cell averaged during the filtering process. A 5-m buffer was created around all buildings, roadways, and extraneous features, using information provided by the Beale AFB environmental GIS group, to mask surface features in the DEM known to affect any further depression analysis.

This procedure creates a detailed grid of micro-depression elevations and precise locations of potential vernal pools and complexes within the DEM that were filled or “smoothed” during the averaging process. Depressions with depths of at least 10 cm were selected for further evaluation. These data were then smoothed again using a majority analysis in a 10-m boxcar moving-window-average filter. Since this technique looks for significant differences in topography within a small area, the calculated grid values for the 10-cm depression features often include areas such as buildings, trees, and other objects that were unmapped. Known large-scale false positives were removed manually during the initial process, but those that could not be identified as false positives will be investigated and identified during later field delineation efforts. The boundaries of the depression features from this analysis were then extracted, and ESRI format shapefiles were generated.

5 RESULTS AND DISCUSSION

The IKONOS vernal pool detection map (Fig. 7) and LiDAR-derived depression results were ultimately combined within a GIS to create a high-certainty vernal pool identification map. To generate this map, the final results from the supervised image classification and the results from the LiDAR depression analysis were intersected. LiDAR areas with surface depressions that exceeded 10 cm and were also detected in the multispectral analysis were retained as positive vernal pool detections. Regions that did not meet both of these criteria were removed from any further analysis or consideration as possible vernal pools. For example, an area that was identified as a vernal pool in the multispectral analysis but that did not have a surface depression greater than 10 cm was dropped from the final mapping results. This analysis was highly effective in eliminating numerous false detections in each of the individual multispectral and LiDAR analyses.

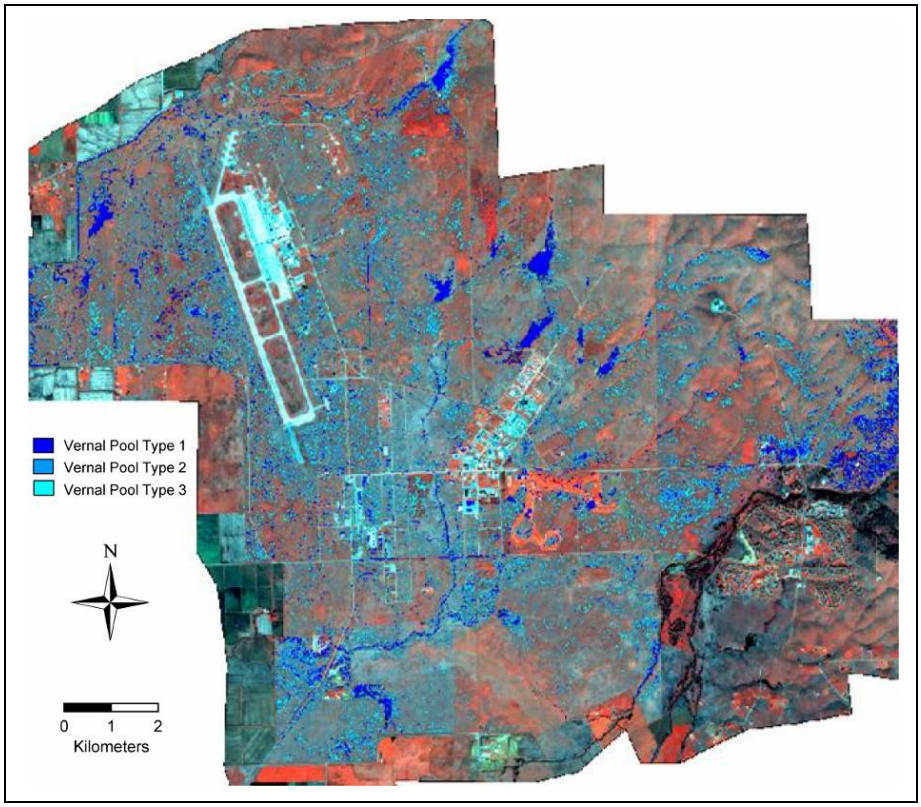


Figure 7. Supervised image classification results (IKONOS) depicting vernal pool detection results.

Figure 8 is an overview of the final vernal pool detection map derived from the combined MSI–LiDAR analyses. Individually the multispectral analysis identified approximately 11.5 million square meters of area as potential vernal pools (Table 1). When multispectral results were intersected with the LiDAR-derived depressions, this number was reduced to a more realistic 4.1 million square meters, representing approximately 35.6% of the original multispectral detections. Of particular interest is the

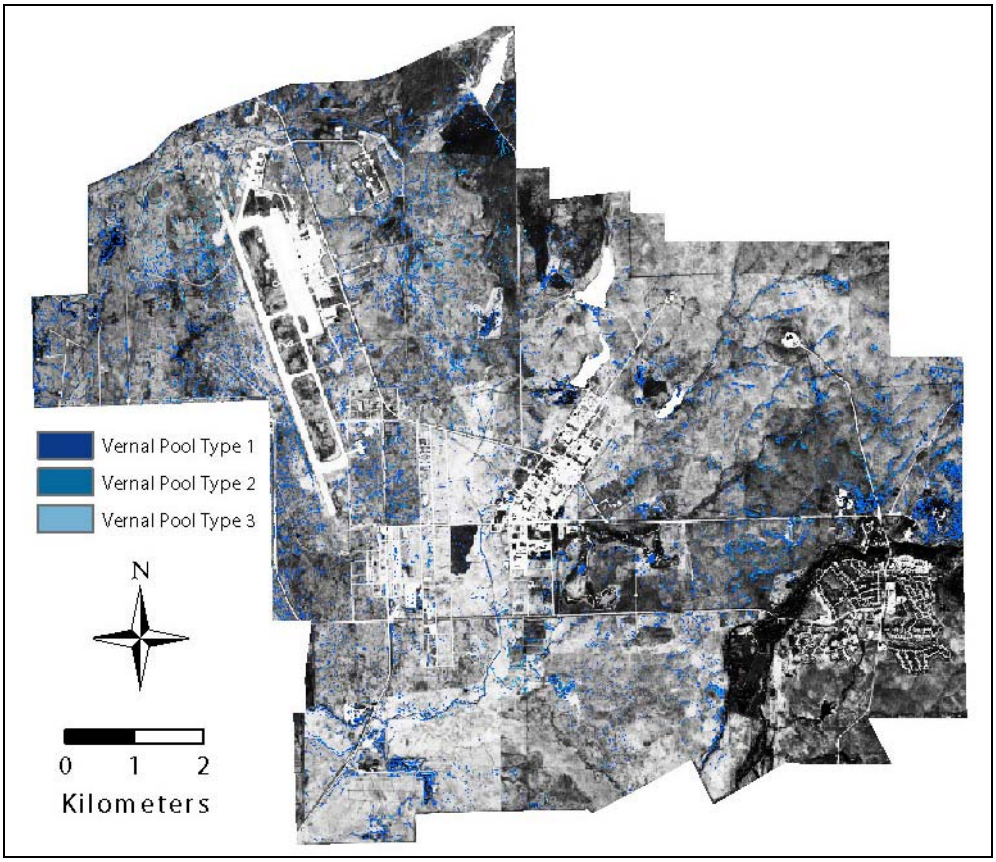


Figure 8. Final intersected MSI- LiDAR vernal pool detection map.

Table 1. Vernal pool areas derived from the MSI classification, LiDAR depression analysis intersection results, and percent vernal pools retained following the MSI–LiDAR intersection analysis.

Classification categories	Multispectral vernal pools (m^2)	MSI–LiDAR vernal pools (m^2)	% retained
Vernal Pool Type 1	3,097,131	1,543,929	49.9%
Vernal Pool Type 2	5,830,532	1,818,120	31.2%
Vernal Pool Type 3	2,607,362	753,795	28.9%
Total	**11,535,025**	**4,115,844**	**35.7%**

high percentage of vernal pools retained for those labeled Type 1 (highest probability), approximately 50%. These numbers support the conclusion that the spectral signature derived for Type 1 vernal pools (Fig. 6) shows the highest reliability for determining the location of vernal pools within multispectral imagery.

Overall the multispectral image classification located features most similar to those previously mapped in the field but was also able to classify them into similar groupings (e.g. Type 1) (Table 2). Furthermore, additional aquatic resources were identified that were not included in the original field data. These additional aquatic resources were primarily identified as Type 2 (medium probability) and Type 3 (low probability). The latter two groups may represent other vernal pool features, including potential jurisdictional vernal pool resources or other anomalies, both in the field and in the remotely sensed data. Because of the difference in the labeling of types in the human-derived classification versus the remote sensing classification based on wavelength, etc., only the total summed estimates of size can be compared. The image classification effort increased the vernal pool feature area by 169% over the field-identified pools and swales. This large increase is attributed to several causes:

- No matter how large a field effort is undertaken, it is not possible to find every minor depression that may have vernal pool features;
- The image processing located both wet soils and similar vegetation signatures also as vernal pool features, but these signatures independently may not be valid vernal pool features in the field; and
- Some of the sites located may only pool water in more extreme climatic conditions but may still maintain a signature of interest.

Table 2. GIS-derived areas of previous mapping efforts to determine the extent of vernal pools.

Previous mapping	Area (m^2)
Vernal pools	1,432,557
Seasonal swales	469,313
Other seasonal	392,076
Disturbed seasonal	146,182
Total	2,440,128

6 SUMMARY

The results from this remote sensing analysis are critical for the next phases of the SAMP study. These results will allow a more accurate field survey and delineation and the ability to focus on all features located and not just those encountered when physically walking transects. GIS technology allows the field-mapped areas and the pool locations from the remote sensing efforts to be sorted into useful field sampling populations (Fig. 9). Likewise, a field verification effort can be done using statistical sampling approaches to describe those features meeting jurisdictional requirement as well as other ecological features of interest necessary to the next phase of the study. Additionally, after field verification and sampling of pools, a vernal pool classification based on species composition may be possible. By using the identified resources in three types as described in this study, a highly efficient field wetland delineation can be accomplished. Also, by identifying all swales and possible hydrological connections, these data can support a wetland functional analysis of the relationships at the pool-to-pool, pool-to-swale, pool-to-small-scale-watershed levels.

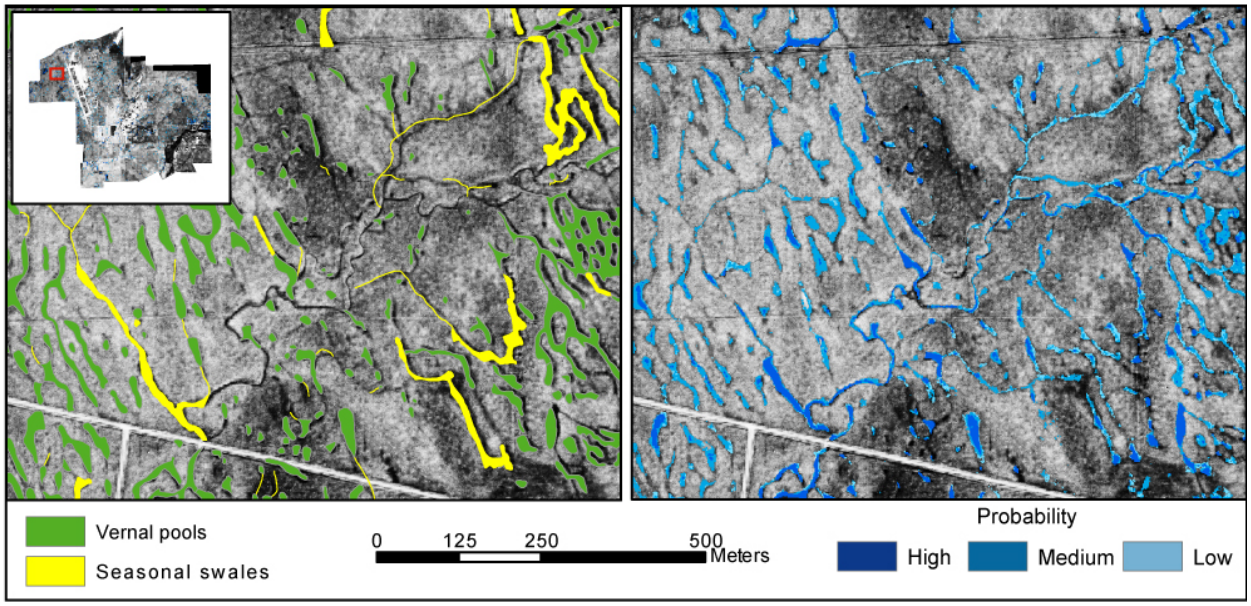


Figure 9. Close-up comparison of field-derived vernal pool and swale boundaries (left) and final MSI-LiDAR-derived vernal pool detections (right).

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
July 2006

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Delineating and Evaluating Vegetation Conditions of Vernal Pools Using Spaceborne and Airborne Remote Sensing Techniques, Beale Air Force Base, CA

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Robert W. Lichvar, David C. Finnegan, Stephen Newman, and Walter Ochs

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL TN-06-3

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Air Force
Beale AFB

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Remote sensing techniques were employed to identify aquatic resources, including vernal pools and riparian areas, at Beale Air Force Base (AFB) in September 2005. Aquatic resources previously identified at Beale AFB were delineated in the field and precisely located with a global position system (GPS). Though precise, these GPS maps were not comprehensive enough to fully understand the distribution and character of the aquatic system. Using those field results, we developed techniques to identify these and similar locations using digitally derived spectral signatures from IKONOS high-resolution multispectral imagery. To refine the delineation results obtained from the multispectral imagery, high-resolution topographic data were acquired over the study area using NASA's Airborne Topographic Mapper (ATM) waveform LiDAR. Using the post-processed digital elevation models (DEM) and a series of statistical approaches, we eliminated many false positive identifications and developed a comprehensive Geographic Information System (GIS) based set of maps for three distinct groupings of vernal pools. These groupings were rated from most similar to previously field-identified vernal pools, to areas with moderate probability to be similar and least similar but still considered areas of interest. The original field mapping results located 244.0 ha of vernal pools and swales; our remote sensing efforts found 411.5 ha. This represents a 169% increase in potential vernal pool locations over the previous estimate.

15. SUBJECT TERMS

Aquatic resources
Beale Air Force Base
Remote sensing
Vernal pools

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
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