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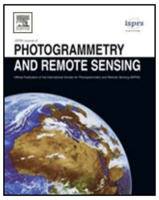

GIS applications for military operations in coastal zones

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ABSTRACT

In order to successfully support current and future US military operations in coastal zones, geospatial information must be rapidly integrated and analyzed to meet ongoing force structure evolution and new mission directives. Coastal zones in a military-operational environment are complex regions that include sea, land and air features that demand high-volume databases of extreme detail within relatively narrow geographic corridors. Static products in the form of analog maps at varying scales traditionally have been used by military commanders and their operational planners. The rapidly changing battlefield of 21st Century warfare, however, demands dynamic mapping solutions. Commercial geographic information system (GIS) software for military-specific applications is now being developed and employed with digital databases to provide customized digital maps of variable scale, content and symbolization tailored to unique demands of military units. Research conducted by the Center for Remote Sensing and Mapping Science at the University of Georgia demonstrated the utility of GIS-based analysis and digital map creation when developing large-scale (1:10,000) products from littoral warfare databases. The methodology employed – selection of data sources (including high resolution commercial images and Lidar), establishment of analysis/modeling parameters, conduct of vehicle mobility analysis, development of models and generation of products (such as a continuous sea–land DEM and geo-visualization of changing shorelines with tidal levels) – is discussed. Based on observations and identified needs from the National Geospatial-Intelligence Agency, formerly the National Imagery and Mapping Agency, and the Department of Defense, prototype GIS models for military operations in sea, land and air environments were created from multiple data sets of a study area at US Marine Corps Base Camp Lejeune, North Carolina. Results of these models, along with methodologies for developing large-scale littoral warfare databases, aid the National Geospatial-Intelligence Agency in meeting littoral warfare analysis, modeling and map generation requirements for US military organizations.

1. Introduction

The US military is undergoing tremendous change in order to capitalize on information-age technologies. Through network-centric technologies, leaders are now beginning to apply digital data depicting real-time information about military situations in regional security environments, thereby improving warfighting assessments and decisions. This information includes dynamic weather, image, map, force structure and logistics conditions (NIMA, 2003) (Fig. 1). United States Marine Corps commanders, in particular, are using these technologies to achieve a better understanding of coastal zones, with specific interest in littoral penetration points (LPPs), a 3–8 km wide lane, extending offshore from the 15 to 20 m depth curve to 5–10 km inland (Welch et al., 2003). Historically, in order for commanders to make assessments about these corridors, tremendous effort was necessary to manually consolidate many different analog products created at varying scales to provide a thorough understanding of the coastal battlefield. Recognizing that a number of studies have addressed independent military solutions using digital geospatial data, the objective of this study is to demonstrate the utility of combining GIS analyses, modeling and map creation from a littoral warfare database for developing large-scale (1:10,000) products that integrate sea, land and air environments.

The need to understand terrain has always been an essential requirement for military commanders. This understanding has

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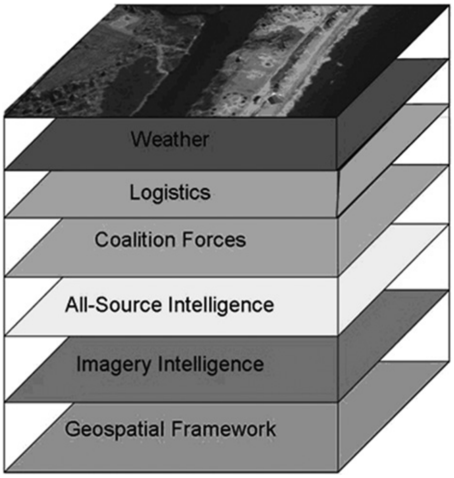

Fig. 1. Fusion of geospatial data on the modern battlefield (from NIMA (2003)).

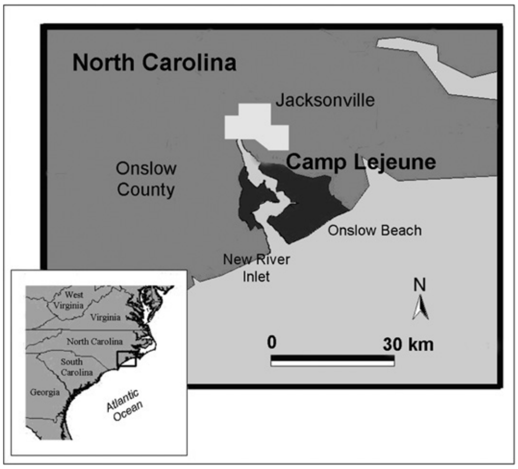

Fig. 2. Camp Lejeune is located on the Atlantic coast of North Carolina.

Fig. 3. QuickBird pan-sharpened image of the study area.

been supported by paper maps enabling military operations for hundreds of years. The imperative to evolve the paper map to the digital environment has included military advances and applications such as motorized vehicles, aircraft, resource assessment and now, digitization (Northrop Grumman, 2002; Bedenbough, 2006). Regardless of the catalyst, the primary need for a map is to support situational awareness; all commanders and their staffs need to understand the battlefield. The map acts as the spatial framework upon which a common situational display is built.

Substantial research efforts are ongoing by the US Department of Defense whereby digitization and use of GIS are being employed to minimize the limitations of analog maps in an attempt to improve combat decision-making (ESRI, 1998). Full digitization of the battlefield, however, will demand the complete embracing of digital geospatial data and the means of exploiting these data with GIS at all levels of war (PEO-C3S, 1997). For the foreseeable future, paper maps and GIS will be complementary, since the military has only been recently using digital data in training and combat — primarily confined to strategic and air systems (JCS, 1997, 1999; Birdwell et al., 2004). Tremendous growth in GIS use is now being realized as the importance of digital technology on the tactical battlefield is recognized. Within the Marine Corps, GIS permits efficient representation of the features found in the ever-changing, littoral battlespace. Spatial databases, the central storage component in a GIS, accommodate the dynamic conditions of these areas by providing benefits such as a uniform repository of geospatial data, rapid data entry and editing, rich feature context, facilitation of dynamic map display and the capability for many users to edit the data simultaneously (Zimmer, 2002). Capitalizing on these benefits and at the direction of the National Geospatial-Intelligence Agency, systems to consolidate GIS technology for military commanders (in all services) – software packages such as the Commercial/Joint Mapping Tool Kit (C/JMTK) and Feature Analyst by Visual Learning Systems – are now being developed (Northrop Grumman, 2002; VLS, 2007). They are designed to be a standardized, commercially-developed, comprehensive tool kit of software components for the management, analysis and visualization of defense-related map and map-related information (ESRI, 2003; VLS, 2007).

The rapid exploitation of feature data is critical to operations in the littoral zone. In this context, proper GIS database design, appropriate analysis procedures and effective product generation are needed to facilitate military decision-making capabilities (Zeiler, 1999). Consequently, this project used many of the same software tools found in the C/JMTK to construct specialized large-scale map products and detailed analyses that demonstrate the application of GIS in providing useful information about the LPP. Based on observations and identified requirements from the National Geospatial-Intelligence Agency and Department of Defense, a GIS combat chart employing models of specific sea, land and air environments was created from multiple data sets of a study area at Camp Lejeune, North Carolina. Similar data sets for US areas of interest around the world exist where the models and methods developed here can be applied. Results of these methodologies for developing large-scale littoral warfare databases will continue to aid the National Geospatial-Intelligence Agency in meeting needs for future missions conducted by the Marine Corps, sister services and governmental agencies. They also are suitable for meeting geospatial needs of resource management, disaster relief and emergency response in coastal areas.

2. Study area

Camp Lejeune is the largest Marine Corps base in the world, occupying an area of 619 km^2 in coastal North Carolina (Fig. 2). Separated from the mainland by the Intracoastal Waterway, the ocean frontage of the base includes 23 km of beach and sand dunes (Pike, 2008). Onslow Beach, a portion of coast extending approximately 10 km north of New River Inlet, is “key terrain” for this study (Fig. 3).

The “sea environment” of the study area for this research extends from the offshore limit of the 15 m depth curve to the onshore limit of the intertidal zone — the region extending along

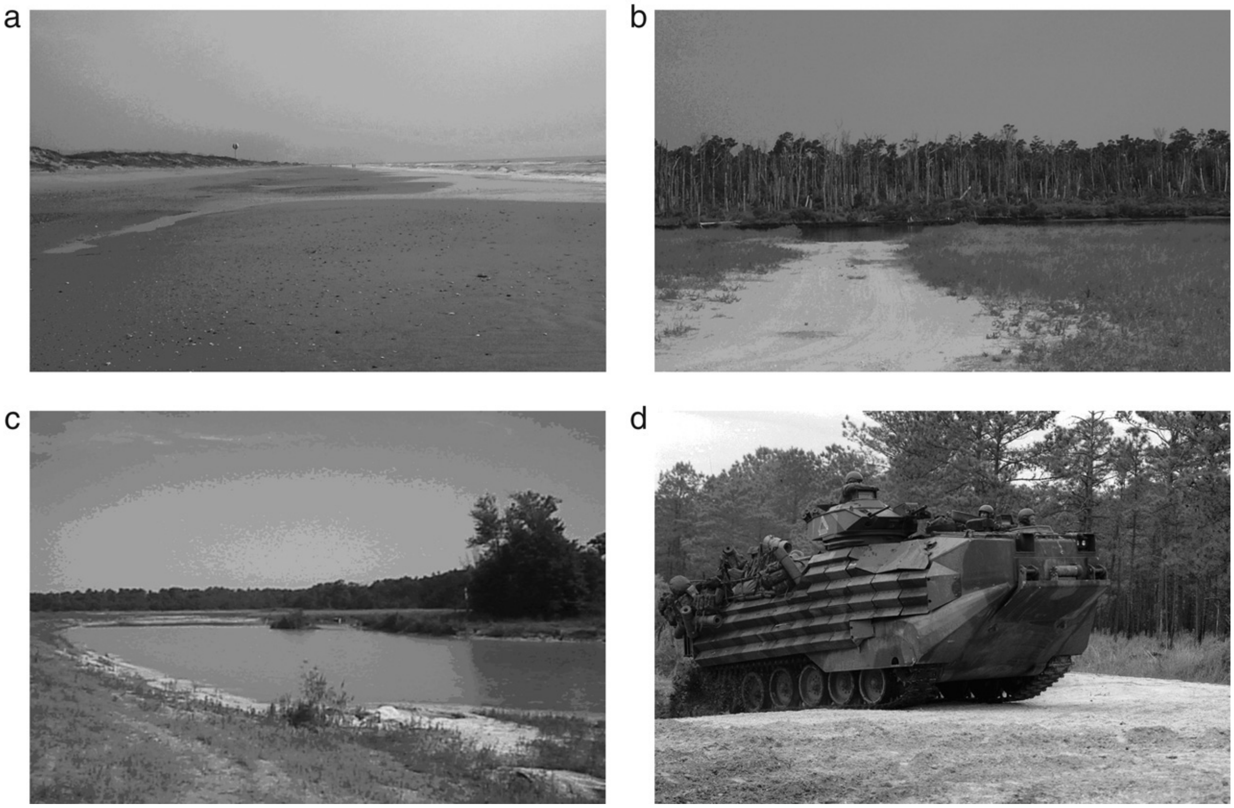

Fig. 4. Onslow Beach at Camp Lejeune slopes gently seaward from a line of 5 m high sand dunes. Beach widths average 70 m from the low water to the dune line (a). Lowlands on the base are characterized by cypress stands, marshes, grasslands and some bare ground (b). Further inland, stands of deciduous and coniferous forests and occasional lakes predominate (c). A well-established transportation network exists, supporting vehicular movement through heavily wooded areas (d).

a shoreline between the high and low waterlines. This zone at Camp Lejeune is characterized by a gently sloping beach gradient of approximately 5° (Fig. 4(a)).

Inland, the study area extends 10 km. West of the sand dunes, the terrain is relatively flat with elevations reaching a maximum of 16 m above mean sea level (MSL). The landscape within 2 km of the coast is interspersed with cypress stands, coastal marshes, bare ground and grasslands (Fig. 4(b)). The soil in these lowlands is predominantly sandy in nature except for the marsh areas where silty soils exist. Further inland (2–10 km from the coast) are modest stands of deciduous and coniferous forests with some small lakes, mixed scrub and grasslands (Fig. 4(c)). Soils here, although sandy in some remote areas, are mainly silty clays and loams. Heavy clay concentrations are rare.

Although the majority of the region is covered by natural features, the study area also includes some cultural features. Small buildings along the beach and other military features exist, including helicopter landing zones, ammunition and equipment storage areas, staging areas and a small airstrip. Additionally, a well-established transportation network that includes a mix of paved and gravel roads, vehicular trails and walking trails interconnects the region. Access from the beach to this network is possible via cross-country exits between sand dune formations. These beach exits connect vehicular trails extending across the Camp Lejeune training area, most of which are suitable for vehicle traffic. In densely forested areas further inland, heavy vehicles are frequently confined to the established transportation networks (Fig. 4(d)) (NIMA, 1998a). Overall, the study area provides a good example of a littoral environment that is capable of supporting amphibious operations and resembles many littoral regions around the world currently of interest by the Department of Defense. Lessons learned and products developed here, therefore, can be applied globally to military, as well as civilian assessments in other coastal areas.

3. Methodology

A procedure for demonstrating the effective use of GIS in generating large-scale products from littoral warfare databases employing commercial GIS software was developed. Three basic steps were involved: (1) database preparation; (2) map product design; and (3) development of GIS applications for littoral operations.

3.1. Database preparation

The National Geospatial-Intelligence Agency, Marine Corps and Naval Oceanographic Office provided data for this project and database preparation was the initial task. This task required definition of the area of study and the collection, sorting and inventory of existing maps, database and remote sensing source materials. Given the increasing availability of geospatial data on the web, military and civilian GIS users alike are finding the need for rapid selection, organization and assessment of data for particular applications. In this case, index sheets for maps and photographs that provide a ready reference were prepared and various data sets that give the most up-to-date information about the LPP identified. The data sets for this project were organized into map/database and remote sensing data totaling over 18 GB of digital files. These data are discussed below.

3.1.1. Maps and GIS databases

Maps and GIS database products used in this research are listed in Table 1. The National Geospatial-Intelligence Agency contributed the National Imagery and Mapping Agency and US Geological Survey (USGS) paper maps at scales of 1:50,000 and 1:24,000; the Naval Oceanographic Office provided National Oceanic and

Table 1
Camp Lejeune map and database products.

Map and database products
Camp Lejeune's Integrated Geographic Information Repository (GISO, 2001)
NIMA LWD[a] Prototype 2 data set (NIMA, 1998a)
LWD Specifications and Feature List found in 11 different feature categories (each identified with a Feature Attribute Coding Catalog (FACC) number) (Chan, 1999)
DIGEST/FACC Version 2.1 (NIMA, 2000)
USGS/NGA[a] map and chart products (1:50,000 and 1:24,000 scale)
NOAA Digital Nautical Charts (1:80,000 scale)

[a] (NIMA) National Imagery and Mapping Agency; (LWD) Littoral Warfare Database; (NGA) National Geospatial-Intelligence Agency.

Atmospheric Administration (NOAA) charts produced at varying scales. The GIS data were provided primarily by the Marine Corps at Camp Lejeune. The Integrated Geographic Information Repository is a local GIS database designed to integrate geographic information about Camp Lejeune into one shared resource that serves as a strategic component of the base's information infrastructure (GISO, 2001). This Repository has evolved over the last ten years and now provides comprehensive data on environmental features, natural/cultural resources, military training facilities, communications and security and disaster preparedness requirements. The Littoral Warfare Database Prototype 2 data set from the National Imagery and Mapping Agency and the National Elevation Dataset produced by the USGS were provided by the National Geospatial-Intelligence Agency and incorporated into the project as additional sources (NIMA, 1998a). Both were leveraged in the construction of a sea–land digital elevation model (DEM), the former serving as a resource for bathymetric data, whereas the National Elevation Dataset was used in establishing elevations for the land portion of the study area.

3.1.2. *Image data*

The majority of image data used in this research were high-resolution satellite images from QuickBird and Ikonos (Table 2). Additional satellite images from SPOT and Landsat also were periodically referenced. From these panchromatic and multispectral scenes, ERDAS Imagine software was used to create four pan-sharpened images. QuickBird panchromatic and multispectral images were merged, producing a multispectral image with 0.6 m spatial resolution. This same procedure was followed with Ikonos panchromatic and multispectral images, yielding a 1 m multispectral image. Finally, a Landsat panchromatic image was merged with both a Landsat multispectral image and a SPOT multispectral image, resulting in two multispectral images, each with 15 m spatial resolution (Fleming and Jordan, 2007). Lidar data with 3 m post-spacing obtained over a portion of the Camp Lejeune coastline were used in the development of a current, continuous elevation data set. United States Geological Survey digital orthophoto quarter quadrangles (DOQQs) and scanned true color/color-infrared aerial photographs were used to complement the satellite images. Finally, ground photographs were collected and integrated into the reference image data set.

3.1.3. *Sea–land DEM*

A primary requirement for the construction of detailed maps and the preparation of GIS analyses of the LPP was the availability of a continuous sea–land DEM of reasonable accuracy. Unfortunately, although data sources as noted in Table 3 existed for the sea, intertidal zone and land areas of the LPP, they were referenced to different horizontal datums and the vertical (bathymetric and elevation) values were not referenced to a common sea level. More importantly, at large-scale, coastline topography frequently shifts due to tide and seasonal climate dynamics and often results in poorly represented intertidal zones. Thus, one of the initial tasks was to integrate the data sets to produce a *current* sea–land DEM. A more detailed description of the process highlighted here can be found in Welch et al. (2003).

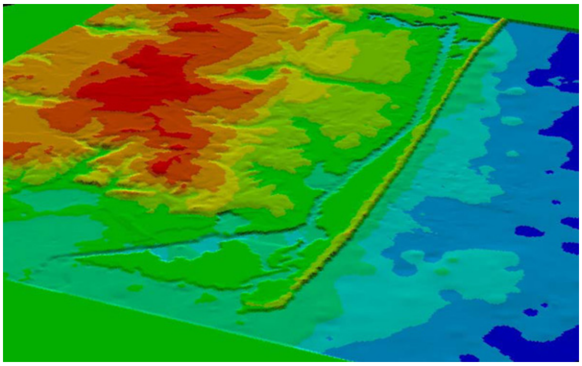

Fig. 5. The sea–land DEM (looking north along the coast) was compiled from the best available elevation and bathymetric data for the study area and represents a continuous elevation model that is suitable for LPP analysis. In this figure, blue shades define bathymetric elevations, the lightest shade of green approximates intertidal zone elevations and darker greens through red detail the land elevations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Integration of the DEM was accomplished by first converting all horizontal coordinates to the WGS 84/NAD 83 datum, and vertical coordinates to mean sea level. In the latter case, depth soundings of varying density obtained from the Littoral Warfare Database Prototype 2 data set for the channel of New River and the ocean area between the 15 m depth curve and Onslow Beach were subjected to interpolation using a Kriging algorithm to create a regular 10 m grid of bathymetric data. Because the zero elevation for these data was mean low water – on average, 0.59 m below mean sea level – a constant of 0.59 m was added to bathymetric values in order to "raise" them to mean sea level. A mean sea level shoreline, which did not exist in the Littoral Warfare Database Prototype 2 data set, was then produced by manually digitizing the waterline depicted on a rectified panchromatic Ikonos image acquired at the time of mid-tide on May 4, 2000.

A digital surface model (DSM) for the intertidal zone along Onslow Beach was produced from Lidar data recorded by the National Aeronautic and Space Administration (NASA)/NOAA from an aircraft operating at 700 m above mean sea level. The Lidar data were referenced to mean sea level. A median filter was employed to remove spikes caused by buildings and trees, leaving a DSM that closely approximates a DEM for the intertidal zone and coastal region inland to the Intracoastal Waterway.

The DEM for the inland portion of the study area was extracted from the USGS National Elevation Dataset data referenced to mean sea level (USGS, 2003). Because significant morphologic changes had occurred along the beach and at the mouth of the New River since the topographic maps were produced in 1952 (USGS, 1952), the values from this DEM seaward from the Intracoastal Waterway to mean sea level were "masked" by the intertidal zone DEM to create a merged inland/intertidal zone DEM. This DEM was then mosaicked with the bathymetric DEM. The resulting continuous sea–land DEM retained bathymetry data from mean sea level seaward, Lidar data from mean sea level to the Intracoastal Waterway and National Elevation Dataset data from the Intracoastal Waterway inland (Fig. 5).

4. Development of GIS applications for littoral operations

Maps and associated database products provide a basis for GIS modeling and the generation of critical information needed by Marine commanders. These modeling results can be included as

Table 2
Camp Lejeune remote sensing products.

Remote sensing data products	Spatial resolution	Date collected
Space imaging Ikonos images (panchromatic/multispectral)	1 m/4 m	May 2000
DigitalGlobe QuickBird images (panchromatic/multispectral)	0.6 m/2.5 m	May 2003
SPOT4 images (panchromatic)	10 m	Sept 1994
Derived SPOT4 and Landsat ETM + multispectral image data	15 m	Sept 1999
USGS digital orthophoto quarter quadrangles (DOQQs)	~1 m	Sept 2001
Lidar data	3 m	Aug 2003
Scanned color and color-infrared air photos (1:10,000 scale)	0.15 m	Sept 1999
USGS NAPP[a] air photos (1:40,000 scale)	1.2 m	Sept 1999

[a] (NAPP) National Aerial Photography Program.

Table 3
Bathymetric and Elevation Data Sets Contributing to the Sea–land DEM (MSL = mean sea level, MLW = mean low water, MLLW = mean low-low water).

Data set	Format	Source	Resolution	Elevation ref.	Vertical datum	Horiz. datum
Littoral Warfare Data Prototype 2 level A	Soundings	NAVOCEANO[a]	Variable (points)	MSL	NAVD 88	NAD 83
Littoral Warfare Data Prototype 2 level B	Land contours	NIMA[a]	Vector	MLW	NAVD 88	NAD 83
National Elevation Dataset (NED)	Grid	1952 USGS Topo Maps	30 m	MSL	NAVD 88	NAD 27
Digital Nautical Chart (DNC)	Soundings	NOAA Charts	Variable (points)	MLW	NAVD 88	WGS 84
Lidar	Grid	NASA/NOAA Aircraft	3 m	MLLW	NAVD 88	None

[a] (NIMA) National Imagery and Mapping Agency; (NAVOCEANO) Naval Oceanographic Office.

inset maps along with vertical and perspective aerial views of LPPs on combat charts. Examples of GIS analysis with the Camp Lejeune data sets are provided here for the sea, land and air environments. Specifically, these examples include: (1) modeling sea level and shorelines in the littoral zone; (2) vegetation and vehicle mobility assessments; and (3) aerial perspective scenes and fly-over animations.

4.1. Modeling sea level and shorelines in the littoral zone

Although shoreward operations are important, getting to shore is arguably the more critical of the two. In this context, mobility in and around the shoreline is a significant challenge to Marine commanders and their planning staffs.

Assessing entry points in intertidal zones is not a new problem for the Marine Corps, dramatically illustrated by a brief review of the Battle of Tarawa (November '43/Central Pacific Campaign in WWII) where some 1500 men were either killed or wounded during the landing at Red Beach 2. Most of these casualties occurred when trying to transition the Marines from "afloat to afoot" with major difficulty due, in large part, to failures in comprehending the effects of the irregular tides on the barrier reef surrounding Tarawa Atoll (Ballendorf, 2002).

GIS-based modeling offers tremendous potential towards providing a basis for understanding the dramatically changing conditions of this critical region of military operations (Millett and Evans, 2002). In this study, two products were generated through integration and modeling techniques using ArcGIS and Imagine software: (1) shoreline delineations; and (2) perspective scenes of tide levels.

The shoreline, as drawn on a typical map, is represented as a single line that is usually tied to a nominal location of the water–land interface at mean sea level (Di et al., 2001; Ingham, 1992). However, this line is only accurate three to four times each day, depending upon local tidal flow conditions (NOAA, 1997, 2003). In actuality, changing tides in coastal environments results in different shorelines depending upon the scale at which the data are viewed (NOAA, 2003). Critical to tactical operations in the littoral environment, planimetric mapping at large scale (1:1000–1:10,000) must include the correct delineation of all intertidal features. The use of multiple lines and various color shades (e.g., yellow indicating sand on the beach) can effectively define the shorelines associated with different tidal conditions and the changing variations of exposed beach areas.

In order to define multiple shorelines reflecting tidal conditions at Camp Lejeune, a model of the intertidal zone was created which enabled visualization of tidal effects on the beach area. A reference image (QuickBird Panchromatic) was draped over the sea–land DEM that had been re-sampled to 1 m post spacing. The draped image was then viewed orthogonally from a projected height of 200 m above ground level (Fig. 6). On 20 May 2003 (date of image collection), the tidal range from mean low water to mean high water was 0.68 m. Using the Imagine Floodwater Module, different tide stages ranging the full tidal range from 0.34 m below to 0.34 m above mean sea level (Δ of 0.68 m) were portrayed (ERDAS, 2000). This module allows one to simulate "filling" a DEM "with water" to selected elevation levels. In Fig. 6, for example, light green shading indicates the mean sea level fill level established using the flywheel function of the Floodwater Module. The software was then employed to adjust the water fill to 0.34 m above and below mean sea level. At each fill stage, vectors of the shoreline were collected by tracing the coastline on the screen display. These unique vectors depicting different tidal stages where then imported into ArcGIS and employed to produce cartographic representations of the changing shoreline (Fig. 7). The darker yellow area represents the beach area between mean low water and mean sea level, while the lighter yellow area represents the beach area between mean sea level and mean high water. Upon viewing such a map with multiple shorelines depicted, commanders can readily determine where tide levels (as a function of beach slope and tidal range) support and/or deter amphibious operations.

Some commanders prefer visualizing the battlefield over interpreting what the battlefield may look like from a map. In an attempt to meet this requirement, perspective views were created of the LPP in order to demonstrate the capability of GIS technology in rendering visualizations of tidal effects on the beach area. In this simulation, a 1 m pan-sharpened, color-infrared Ikonos image (acquired in May 2000) was draped over the sea–land DEM.

Scenes were observed from a viewpoint 30 m above ground level with a view angle of 45° to grid north. Again, employing the Floodwater flywheel function, a tidal range was evaluated from 2 m below to 2 m above mean sea level. This low elevation (2 m below mean sea level) was determined by combining the lowest low-tide mark at Camp Lejeune during May 2000 (−0.59 m) with the average Landing Craft Utility draft depth (~1.4 m). The high elevation (2 m above mean sea level) was approximated by estimating a tidal surge during a spring tide condition. Snapshots

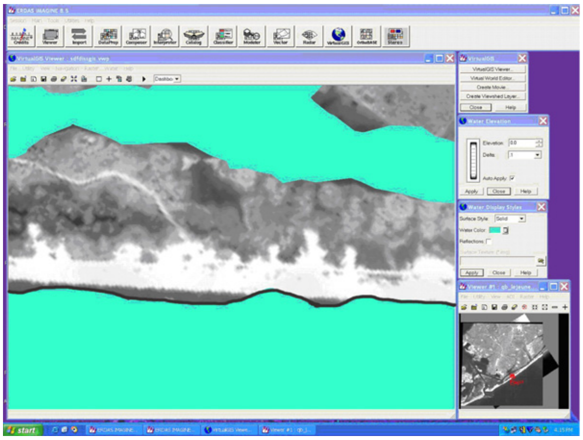

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Fig. 6. Mean sea level tidal stage “filled” using ERDAS imagine floodwater model.

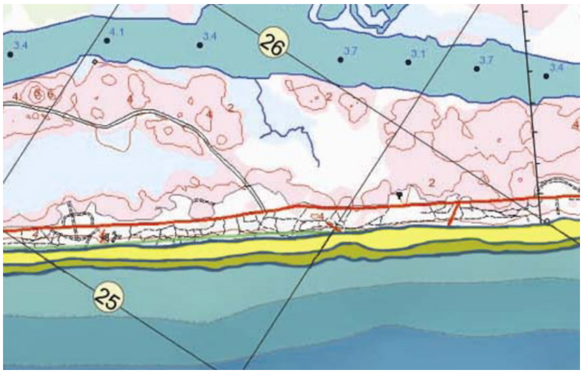

Fig. 7. Tide stages on Onslow Beach. Light yellow shading on the beach represents the beach from mean sea level up to the mean high water line; the dark yellow shading represents beach from mean sea level down to the mean low water line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

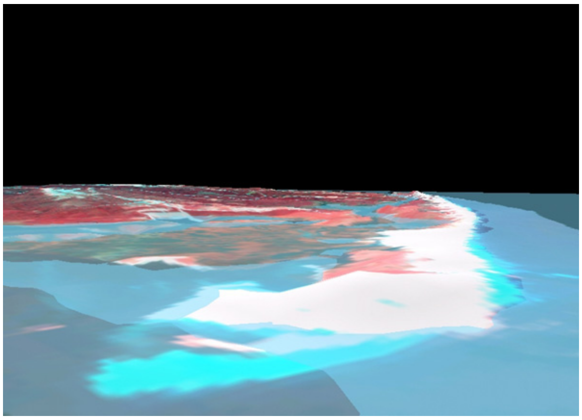

Fig. 8. Mean sea level tidal stage is illustrated in this Virtual GIS 3-D flood simulation. This type of visualization is useful for determining areas that may be exposed or treacherous at different times during a given day. It is also possible to assess errors or inconsistencies in the DEM that should be addressed and corrected.

(“screen captures”) were collected to depict the change in water levels for the different tidal stages (Fig. 8). These types of images reveal overland flow of tidal waters at the proposed LPP, enabling decision-makers to readily visualize (in 3-D) where water levels affect amphibious operations.

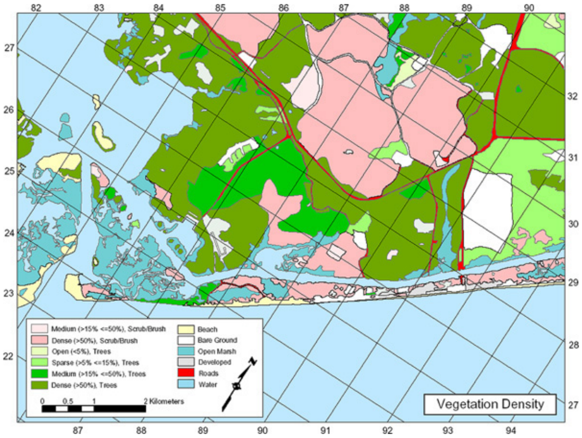

Fig. 9. Vegetation density was derived from the vegetation and land cover layers of the GIS database.

4.2. Vegetation cover and vehicle mobility

Vehicle mobility – how well a unit’s mounted force can traverse terrain – is a major concern to Marine ground commanders. Vehicle mobility in relatively flat terrain is primarily a function of vegetation density and soil trafficability (Department of the Army, 1994). In terrain where dramatic elevation change exists, slope becomes an additional consideration and mandates the use of an elevation model. Since the Camp Lejeune area has very little relief, only two unique products were necessary to assess vehicle mobility using ArcGIS software: (1) a vegetation density map; and (2) a soil trafficability map.

A map categorizing tree and shrub density with respect to heavy vehicle movement – the vegetation density map – was produced first using information contained in Camp Lejeune’s Littoral Warfare Database Prototype 2 and augmented by manual photointerpretation of color-infrared digital orthophotos (pixel size = 1.2 m) prepared from aerial photographs acquired in March of 1998 (NIMA, 1998a). Tree size and density are critical factors of concern for vehicular movement. Specifically, large trees growing close together and/or smaller yet very dense vegetation can restrict the movement of wheeled and, in some cases, tracked vehicles. A visit to Camp Lejeune was made by University of Georgia personnel in August 2002 to examine the study area in order to validate the interpretation work and verify the data in the Littoral Warfare Database.

Vegetation density for large trees at least six inches in diameter at breast height (dbh) was assessed as dense (>50% coverage), medium (>15% to <=50% coverage), sparse (>5% to <=15% coverage) or open (<=5% coverage). Scrub/brush density (with dbh generally less than 15 cm) was likewise assessed as dense, medium, sparse or open. Non-forested areas were classified as beach, bare ground, open marsh, developed, roads or water to provide information on the relative openness of the ground cover. The resulting vegetation density map provides information on cover and concealment as well as limits to vehicular movement inland from the initial beachhead (Fig. 9).

Soils were evaluated for their ability to support the weight of tracked vehicles (trafficability) under *wet* conditions typical of those likely to be encountered during the month of May, the month in which most of the image data over the area were collected. In May, rainfall at Camp Lejeune averages about 4 in.

Based on information on soils trafficability provided in “Planning and Design of Roads, Airfields and Heliports in the Theater of Operations”, soil composition (sand, silt and clay) and moisture are the major factors influencing substrate support for vehicles as they move along road networks or cross-country over

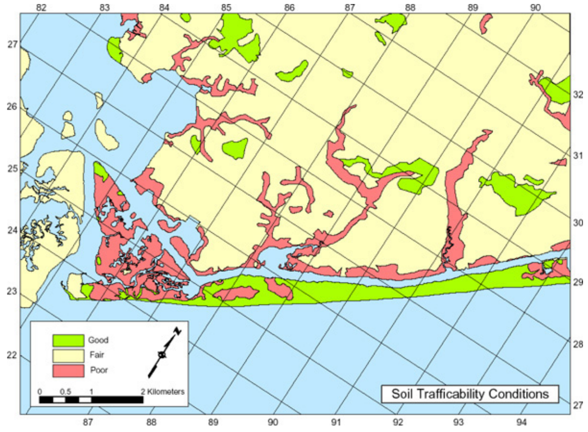

Fig. 10. Reclassification of the soils data layer provided data on soil trafficability under wet conditions.

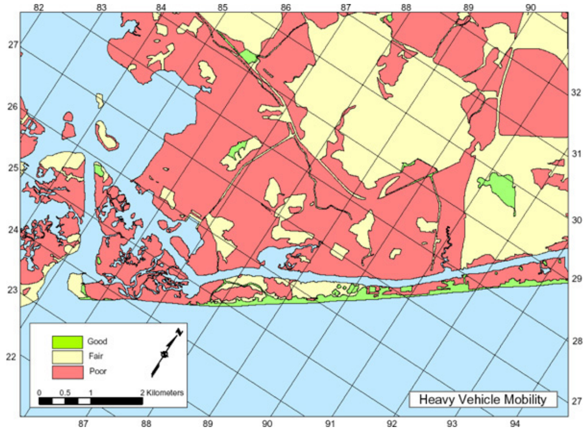

Fig. 11. A heavy vehicle mobility map for the Camp Lejeune LPP was generated by combining the vegetation density and soil trafficability data sets using GIS analysis techniques. Arrows indicate a potential axis of advance that maximizes optimal terrain conditions.

relatively flat terrain (Department of the Army, 1994). The majority of the soils found in the Camp Lejeune Littoral Warfare Database Prototype 2 were, in order of soil moisture holding capacity, silty sands, poorly graded sands, well-graded sands and inorganic clays (NIMA, 1998b). A soil textural triangle, which takes into account soil groups and the relative percent of sand, silt and clay of a soil type, was used to assign rule-based ratings of “Good”, “Fair” and “Poor” to areas on the map classified by soil type (USMA, 2001). The map of reclassified soils shows variations in wet soil trafficability in terms of support for heavy vehicles (Fig. 10). The majority of the study area (76%) was deemed “Fair” in terms of soil condition for heavy vehicle trafficability. Only 10% of the study area, coinciding primarily with the beach and dunes, was classed as “Good” trafficability conditions, while 14% was “Poor” due to drainages along creeks and low-lying wetlands.

A final heavy vehicle mobility map for wet conditions was produced by intersecting the vegetation density and soil trafficability maps (Fig. 11). Specifically, areas with medium, sparse or open vegetation (with the exception of marshes) that were spatially coincident with “Good” soils conditions were rated “Good” for heavy vehicle mobility; areas with medium, sparse or open vegetation (with the exception of marshes) coincident with “Fair” soil conditions were rated “Fair”; and areas with any type of vegetation coincident with “Poor” soil conditions, as well as dense vegetation and marshlands, were rated “Poor”. From this GIS analysis, it is evident that a commander’s flexibility for uninhibited movement across the ground area is limited. A Marine commander using this modeling tool would likely deploy heavy vehicles along an axis of advance where good and fair conditions would be maximized (indicated by the arrows on Fig. 11). The mobility map demonstrates the utility of a GIS database, analysis and modeling in a land environment whereby the inherent functions of a GIS enable the generation of an effective product to assist commanders in making decisions about route selection/attack axis.

5. Fly-over animation and map product design

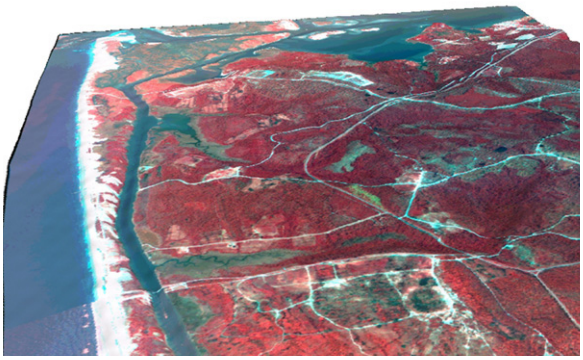

Fig. 12. Aerial perspective view looking southeast along Onslow Beach created by draping a pan-sharpened Ikonos image over the sea–land DEM of the study area. Shown at [a] is the location of Onslow Beach Road.

In the 21st Century, more so than ever before in the history of warfare, sea and land military operations depend on successful air operations. Unmanned aerial vehicles (UAVs) are extremely critical to this end as they provide real-time and near real-time aerial perspective views and fly-overs of the battlefield (Reinhardt et al., 1999; Pike, 2007). When UAVs are not available, however, GIS technology can closely replicate this information for field commanders. Coupled with high-resolution satellite images and/or aerial photographs, the sea–land DEM permitted the development of perspective views and fly-overs for the LPP at Onslow Beach that simulate data return from UAVs. As an illustration of generating a perspective scene, an Ikonos pan-sharpened, color-infrared image (1 m pixel) was draped over the sea–land DEM using the Imagine software (Fig. 12). A vertical exaggeration of 5*x* was applied to the DEM to enhance local relief. This view was generated to simulate a viewing altitude of approximately 350 m above mean sea level with a downward look angle of −31°.

Animation techniques were next employed to simulate UAV fly-overs of the Onslow Beach area created from a sequence of perspective views of the terrain. The first fly-over covered the entire LPP study area analogous to what is termed a limited area of operations for a unit commander. In preparing this product, the sea–land DEM with 10 m post spacing was displayed in Imagine with a vertical exaggeration of 5*x* and draped by a 1 m Ikonos pan-sharpened, color-infrared image. The fly-over parameters were set for an altitude of 200 m, field-of-view (FOV) of 75°, a downward look angle of −31° and a speed varying at rates of 40–110 km/h. A total of 160 frames were generated to provide a movie file (.mov) with a runtime of 90 s that can be viewed on a computer display.

A second fly-over, also saved in movie file format, was generated along the shoreline from Onslow Beach Road to the New River Inlet (USGS, 1952). Color-infrared aerial photographs of 1:40,000 scale scanned at 1.5 m pixel resolution were draped over a DEM with 3 m post spacing produced from the Lidar data. A flight path was established using parameters that included an altitude of 60 m above mean sea level, FOV of 45° and an equivalent ground speed of 40 km/h. A total of 60 frames were generated along the coastline.

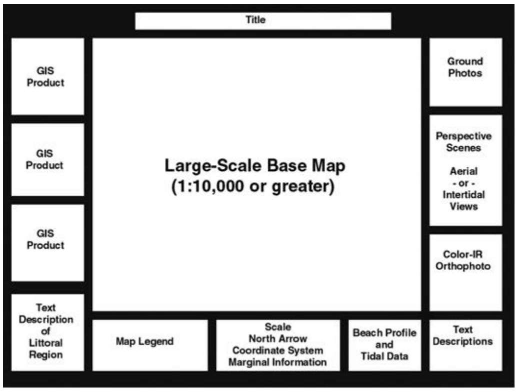

Fig. 13. Template of final map product.

These two fly-overs demonstrated the value of image processing, animation and simulation techniques for visualizing and exploring the battlefield. Aerial perspective scenes and fly-over generation can be quickly compared to real-time (or near real-time) scenes collected by UAVs often under the direction of operational and tactical commanders. Assuming common resolution and view orientation between live UAV video feeds and simulations presented in this research, comparisons should reveal completed or ongoing battlefield changes. The strength of these types of products is the ability to create or replicate airborne visualizations similar to image and video data now available at all levels of command.

Cartographic products that aid in military decision-making must address numerous components of the dynamic battlefield. Information needed and portrayed on maps and through GIS modeling products allow these conditions to be assessed. In this regard, the static military map of years past is not sufficient and a digital product representing the LPP and supported by the GIS applications previously discussed was needed. A graphical layout of such a product was created (Fig. 13). This layout, 153 × 91 cm in size, contains a detailed base map in the middle which serves as the common centerpiece for planning and executing missions *across* levels of command in a fighting force. As considerable detail must be represented and most LPPs will be relatively small areas, scales of 1:10,000 or larger are appropriate, with 1:5000 or larger preferred. Features found in littoral warfare databases were identified and assigned proper codes/symbology on the base map. At a minimum, these include contours (bathymetric and land) at an interval of 2 m and salient features in the intertidal zone and on-shore areas (e.g., waterlines, vegetation cover, wetlands, hydrography, lines of transportation, airfields, cultural features and obstacles).

Since digital and analog map products may be employed by both US and foreign military units, it is desirable to provide coordinate reference systems familiar to all concerned because the need to recover both plane and spherical coordinates compatible with their navigation and fire control systems is critical. For US forces, WGS 84 is the appropriate horizontal datum, with both the Universal Transverse Mercator (UTM) coordinate system and the Military Grid Reference System superimposed at intervals of 100–1000 m, depending on the projected scale of the displayed maps. Both of these plane coordinate systems were included on the layout template. For many allied and coalition forces, spherical coordinates are necessary to effectively employ their weapon systems. Therefore, provisions were made to enable the determination of latitude and longitude values. Perpendicular axes across the map were graduated in degrees, minutes and seconds at 15 s intervals.

Finally, critical information requirements needed by individual operational or tactical commanders in order to accomplish *their* directed missions were deemed important. Products that provide this information can be placed in inserts surrounding the base map (Welch et al., 2003). These marginal data products were developed from the revised littoral warfare database. Included here are: (1) a cross-sectional profile extending from approximately the 10 m depth curve to mean sea level; (2) tide tables for the designated operational period; (3) ground photographs; (4) inset maps at scales of 1:50,000 to 1:250,000 created using GIS analysis functions that depict command-specific applications (e.g., vegetation density, soil trafficability and heavy vehicle mobility); and (5) both vertical and perspective aerial views of the LPP. Ultimately, this template provides a standard format for an operational map where the commander is afforded dynamic updates to on-going missions.

Integrating some of the previously created products, a final map product for the Camp Lejeune LPP was generated (Fig. 14). More details of the production process outlined here are provided in Welch et al. (2003). This final product, displaying multiple decision-making tools concurrently, has been well received by the National Geospatial-Intelligence Agency technical staff and US Marine Corps organizations and is undergoing planned evaluations for operational employment.

6. Conclusion

A number of studies have addressed independent digital solutions for military needs, but few have focused on the merits of generating and integrating GIS-based analysis products into a collective decision-making tool. In this study, a methodology was developed and employed to rapidly integrate and analyze multiple geospatial data sources and create digital/hardcopy maps and visualizations supporting commanders operating in coastal zones. Three major environments found in the littoral region – sea, land and air – were examined.

Many military products make frequent use of a seamless sea–land DEM. It must feature bathymetric and elevation data of sufficient accuracy to permit the generation of waterlines in the intertidal zone for mean low water, mean sea level and mean high water. Establishing data sets that detail bathymetric conditions is more cumbersome than collecting similar data for land areas. Final integration of these data (e.g., bathymetric soundings) with Lidar data of intertidal zones and upland DEMs, each tied to a different vertical reference, can be a difficult and time-consuming task. Recognizing this, defense mapping organizations should prioritize and allocate sensor and assessment resources accordingly, thereby enabling timely collection of bathymetric data followed by efficient integration of all required information.

All three environments – sea, land and air – merit the attention of Marine commanders working in operational environments. Shoreline delineations provide improved maps of intertidal zones at large-scale, detailing how tide levels will impact amphibious operations. Perspective scene modeling of these shorelines reveals overland flow of tidal waters at LPPs, enabling 3-D visualizations of water levels from which conclusions about mission impacts can be made. Effective vehicle trafficability estimates are critical information as well. Geographic information system functions enable the analysis of data vital to operational decisions on best paths from beach to inland deployment. In this regard, proper GIS database construction and data modeling are necessary to assist commanders in route and/or attack axis selection. Finally, aerial perspective scenes and simulated "fly-overs" provide a realistic view of the landscape by draping properly rectified satellite or aerial images over co-registered, detailed and accurate DEMs. These products are quickly compared to real-time (or near real-time) video and scenes collected by UAVs and/or satellite images.

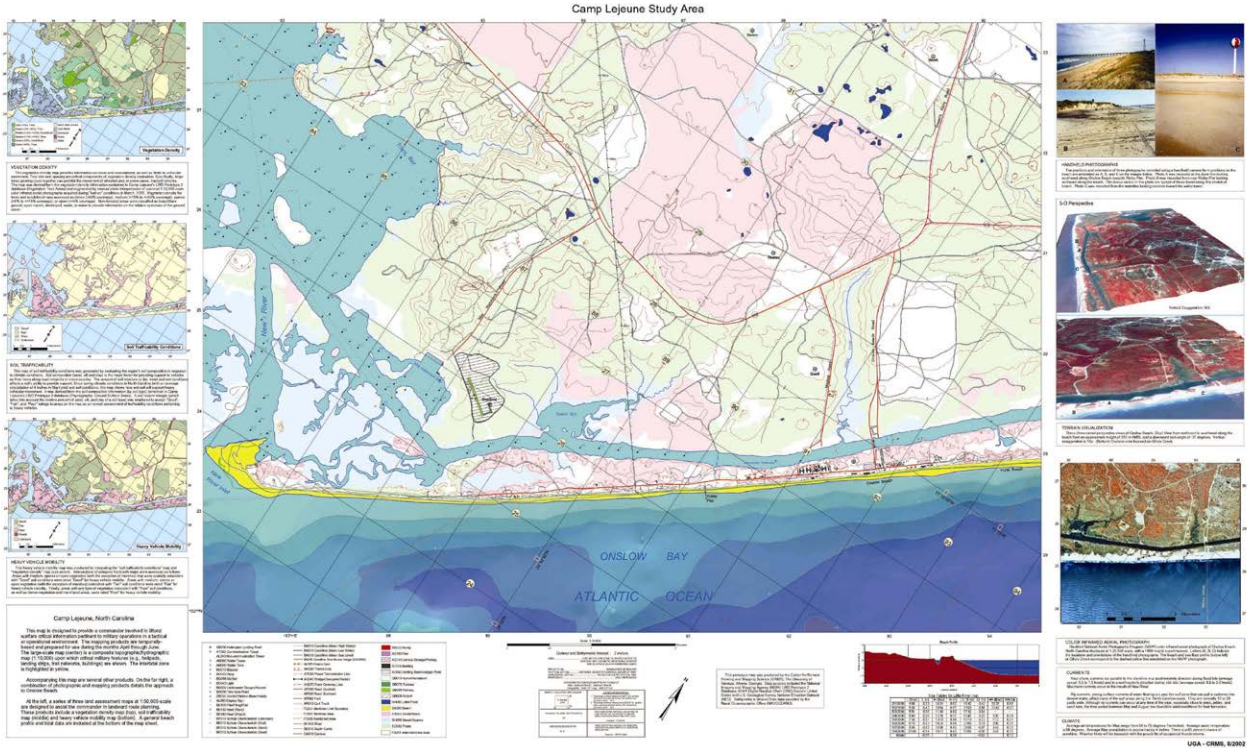

Fig. 14. Example final map product.

The mapping tool used by tactical and operational Marine units should be built around a dynamic large-scale combat chart. The chart must include multiple coordinate systems and proper military features. Supporting the chart, products can be placed around the margin such as tide profiles and tables, ground and aerial photographs/images of significant military objectives, perspective views and inset maps based on required analyses deemed important to operations by commanders.

Analysis and modeling capabilities of a GIS provide military commanders the means to rapidly integrate data sets, assess conditions, plan strategies and evaluate options. The overall success and reliability of large-scale, Littoral Warfare Database products created from image processing and GIS tools ultimately depends on the availability of skilled personnel with ready access to current data. This research provided examples of improved digital data sets, map products and analysis procedures that can be used by the National Geospatial-Intelligence Agency for future Littoral Warfare Database military applications as well as decision support for civilian coastal management, homeland security requirements and disaster relief.

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Classification notice

All of the information and products provided in this document are UNCLASSIFIED. None of the data were classified at the time of use. They remain unclassified as of this publication.

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