Chapter

# Advancing Estuarine Shoreline Change Analysis Using Small Uncrewed Autonomous Systems

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## Abstract

Estuarine shorelines face the threats of accelerating sea-level rise, recurrent storms, and disruptions of natural sediment and ecological adjustments owing to historic human interventions. The growing availability and technical capability of uncrewed systems (UxS), including remote or autonomous aerial and surface vessels, provide new opportunities to study and understand estuarine shoreline changes. This chapter assesses the state of the technology, interdisciplinary science and engineering literature, and presents case studies from the Chesapeake Bay, Virginia, and coastal North Carolina, USA, that demonstrate new insights into coastal geomorphic processes and applications to managing complex and dynamic estuarine shorelines. These technologies enhance the collection of geospatial environmental data, coastal monitoring, reduce spatial uncertainty, and support measurement of alongshore and onshore/offshore sediment fluxes. Case studies in this chapter highlight scientific insights such as shoreline responses to sea-level rise as well as the practical value of these technologies to develop adaptive management solutions such as living shorelines and nature-based features.


**Keywords:** estuarine shorelines, coastal erosion, small uncrewed autonomous systems (sUAS), autonomous surface vessel (ASV), bathymetry

## 1. Introduction

### 1.1 Scientific and coastal management interest in estuarine shorelines

Estuaries comprise some of the most ecologically and economically productive ecosystems in the world. Owing to their inherent admixture of fresh and marine ecosystems, they are attractive to an abundance of living resources and a critical ecosystem at many life stages for fisheries as well as major repositories of carbon in the wider earth system. By virtue of their location, they are also conduits of maritime trade and host to mass urban agglomerations, including coastal megacities. These natural assets and anthropogenic forces of development, however, are frequently in imbalance owing to land development, ditching and draining of wetlands, hardening of shorelines, and direct and indirect effects on ecological flows (nutrient pollution, ground water tables, and hydrodynamic impacts of hydrology and channel dredging). The estuarine land-water interface is also highly variable in spatial pattern, diversity of ecological features, and degree of human impact. With anthropogenic climate change leading to accelerating sea-level rise (SLR), these alterations and the future status of estuarine shorelines and green infrastructure have become a serious concern for sustainable resources and coastal management. Rates of change of SLR, altered tidal currents and frequency-duration of flooding, salinity gradients, and even climate change effects on coastal storms further complicate the prediction of future states and dynamics. Coastal flooding and erosion are expected to accompany climate change [1–3], with the prospect of rapid erosion in estuarine shorelines [4]. Research previously focused on gradational change and cumulative impacts has also prompted new questions on the potential for catastrophic tipping points in estuaries, where thresholds may be exceeded in state variables or nonlinear responses that might rapidly tip systems into new states. Wetland degradation, blue carbon loss, fisheries decline, and salinization of soils with rapid shifts in tidal regimes are but a few examples. Toward addressing these processes and providing data for an ever-quickly shifting baseline, this chapter presents the conceptual framework, selected literature, and case studies applying small uncrewed autonomous systems (sUAS) for estuarine shoreline mapping, monitoring, and management.

Studies of estuarine shorelines have often focused on inventorying, mapping, and classification as necessary scientific steps toward understanding foundational to understanding and management. Coastal erosion studies typically seek to quantify rates of shoreline change, most often erosional, and secondarily to address shoreline accretion and inform adaptive management such as soft or hard stabilization. Observational data are foundational to coastal development permits and management decisions, including gray or hard stabilization such as docks, bulkheads, revetments, breakwaters and jetties, and soft stabilization or greener solutions, including living shorelines, marsh plantings, or erosional setbacks. Where allowed by federal and state policies and regulations, some localities in the United States have explored the use of estuarine coastal setbacks (e.g., the Town of Nags Head, North Carolina, is developing a new estuarine shoreline management plan) [5]. Land loss in some areas such as deltas or peaty shorelines of wave-exposed estuaries prompted critical studies to inventory and derive rates of change and uncertainty. Such empirical data could then parameterize GIS-based models such as the Sea Level Affecting Marshes (SLAMM) model [6] as well as quantitatively assess change rates for management (potentially to include estuarine shoreline setbacks). Shoreline change rates, once quantified, can also be used to inform management strategies such as best management practices and design of living shorelines (see for example [7]) as well as quantify blue carbon stocks and potential habitat losses and net areal changes as a result of wetland migration (i.e., inland marsh boundary shifts vs. shoreline erosion). The spatial dynamics of shoreline changes are especially important in extensive estuaries with highly complex and variable wave energy/openness, freshwater input and salinity, such as the Albemarle-Pamlico Estuarine System (APES) in North Carolina, USA [8].

Natural and Nature-Based (NNB) management strategies are also increasingly sought to adapt estuarine shorelines to increasing coastal hazards and threats to ecosystem services and values. NNB strategies use a multidisciplinary approach to shoreline management that emphasizes the use of nature-made materials, coastal processes, and habitats to protect and restore shorelines. This type of shoreline management utilizes a variety of techniques, such as planting native vegetation, creating and restoring oyster reefs, and installing "living shorelines" and other novel wave-attenuating structures. NNB management can offer a more sustainable and resilient alternative to conventional hard structures, such as bulkheads and revetments. Unlike hard structures, which can impede natural coastal processes, NNB shorelines are designed to incorporate and leverage those processes for greater protection and sustainability. This approach allows for the continuity of the land–water interface and the conservation of valuable ecosystem functions and services provided by coastal wetlands.

Living shorelines are a form of active shoreline management where native vegetation and/or materials (i.e., oyster shell, sand fill) are used to stabilize shorelines. Living shoreline designs often include low-lying sill structures made of a range of materials but, most commonly, bagged loose oyster shell, rock, concrete structures (e.g., reef balls), and bio-core logs. By not impeding coastal processes, living shorelines provide wave damping capacity, allow for suspended sediment to settle out, and the recruitment of ecosystem engineers, like oysters, mussels, and vegetation, that enhance the resilience of the shoreline to erosion, storm surge, and sea-level rise. As with hard structures requiring permits and environmental impact studies for approval, NNB approaches also require observational data ranging from shoreline change rates, projected impacts and project design life expectancy, and plans to assure or mitigate any impacts to existing living resources.

Following these emerging topics and the increasing diversity, volume, and availability of estuarine shoreline data, we sought to address the following research questions:

1. *What ontological characteristics of estuarine shorelines allow or inhibit their study and geospatial analysis using UxS?*

2. *What are current state of the art shoreline geospatial data and analysis techniques that lend themselves to estuarine shoreline change analysis?*

3. *How can small UxS systems be applied to estuaries (do case studies identify potential and pitfalls, e.g., urban tidal creeks, beaches, and living shorelines?)*

Toward addressing these questions, the chapter further outlines the ontological properties of estuarine shorelines in the remaining introduction. Data sources from various platforms are reviewed in Section 2, with subsequent evaluation and critique in Section 3. The emergence of small autonomous systems, including aerial and surface vessels) is described in Section 4. Next, Section 5 tackles research question three using case studies, followed by a discussion of the implications for future scientific and practical estuarine management in Section 6. Finally, Section 7 concludes the chapter by summarizing key findings and future potentials.

### 1.2 Ontology of estuarine shorelines

To apply emerging technologies for coastal science and environmental management, taking stock of the real-world entities and ontology of coastal features is warranted. Estuaries are not merely mixing areas of zones of process interactions but also consist of paleogeomorphology and geologic influence that constrain, in a hierarchical fashion, subsequent, current, and future processes, and ecosystem dynamics. Some estuaries have been termed "give-up" estuaries where sea-level rise overrides an out-of-balance sediment supply from rivers [9]. Other estuaries may "keep up" or even "catch-up" in the case of future increases in sediment supply (e.g., from ocean shoreface or upland erosion). In addition, shorelines, marshes, and subtidal features may respond in complex, dynamic, and threshold-based behaviors such as short-term storm action versus long-term or decadal shifts in storminess superimposed on sea-level changes. Perhaps the most difficult influences on estuaries, human activities are also dynamic, and coastal property and tax base, shoreline erosion/accretion, habitat conservation, riparian and shoreline buffers, and their ecosystem values and services are all affected by coastal zone management policies and decisions. In the Chesapeake Bay of the United States, for example, the regulatory environmental management of estuarine shorelines has federal resource protection requirements that include adjacent ecosystems and habitats (e.g., Chesapeake Bay Preservation Act [10] and protecting adjacent upland and palustrine forests, marshes, SAV and intertidal habitats, and a riparian and shoreline buffer zone, the "Resource Protection Area.") Such management and policies are variable at the federal, state, and local scale in the United States but overall aligned by a mandated "Consistency Doctrine," where shoreline management projects at the federal level must be consistent with approved state jurisdiction coastal management plans.

Given these management alternatives and long-term implications, further scientific and predictive capabilities for estuarine shorelines are valuable. Having robust erosion rates and future shoreline predictions could inform setbacks, conservation easements, downzoning, and Transfer of Development Rights policies. Ecological and environmental management would benefit from having spatial and temporal predictions of shorelines and accommodation space, such as for siting and designing marsh restoration projects and best management practices (BMPs) along estuarine shorelines. Historic aerial photography and nautical charts have been useful resources for estuarine management, but their accuracy and utility in future projections are limited. High-accuracy, high spatial resolution imagery, bathymetry, and environmental conditions from emerging UAS could improve upon these limitations and reduce future uncertainty in shoreline predictions and marsh conditions. Such data can be collected cost-effectively and coordinated with storm events, recovery, and tidal conditions. **Figure 1** presents a conceptual model of an estuary system typical of the Mid-Atlantic and Eastern Seaboard of the United States, such as the Chesapeake Bay and smaller coastal lagoons and sounds from Maryland, Virginia, and North Carolina. The connected habitats and processes shown in the figure highlight commonly sought-after features, such as salt marshes, coastal beaches, dunes, backbarrier habitats, submerged aquatic vegetation, lagoonal bathymetry, freshwater hydrography, and diverse shoreline types and patterns. The conceptual model informs classification, design, and selection of remote monitoring platforms and sensors applicable to each resource or process. Given some coastal lagoons are dynamic and even ephemeral [11] and others are responsive to both punctuated events such as hurricanes as well as long-term sea-level change [12, 13], a synoptic view of the estuarine system is especially helpful to devise mapping and monitoring strategies. Furthermore, these considerations extend beyond the current and historic shoreline, as sea-level rise and watershed processes will affect the future migration of habitats and shoreline changes owing to basin hypsometry and area-elevation relationships [14].

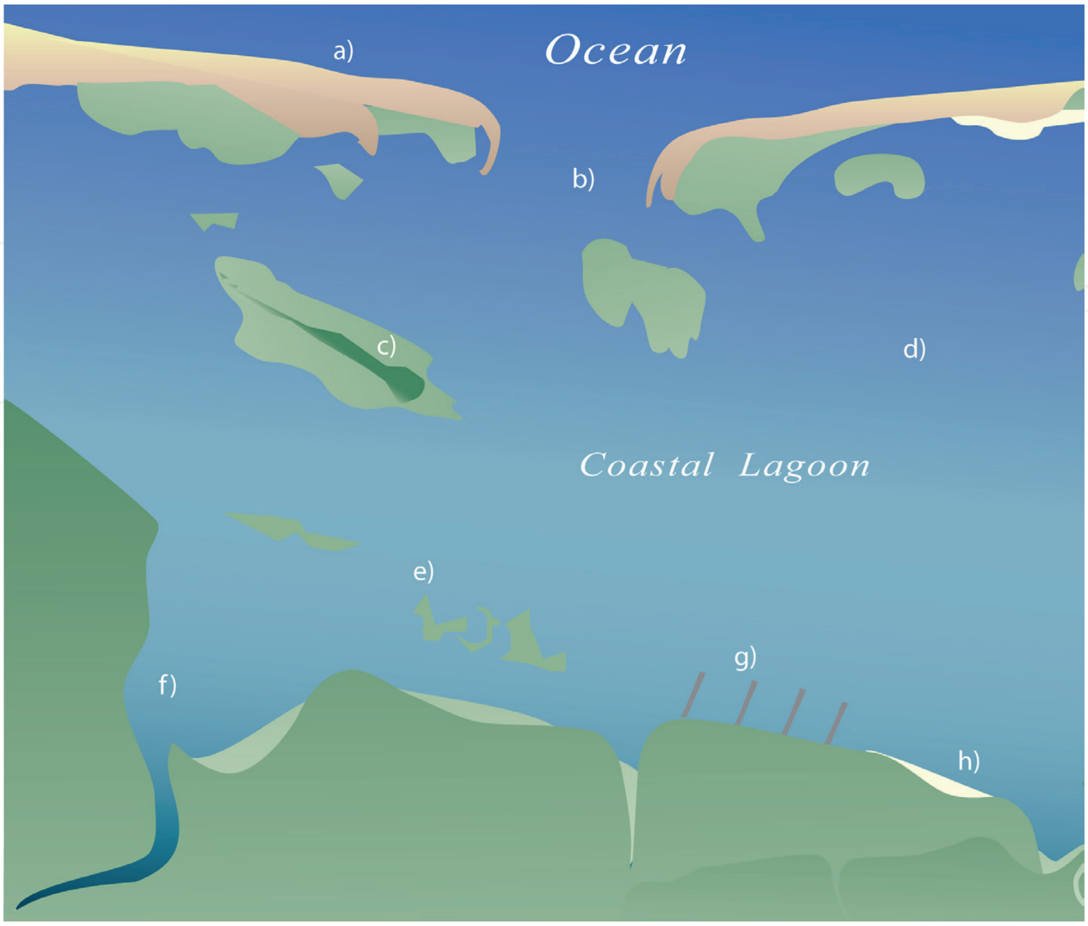


**Figure 1.**
*Conceptual estuary showing a barrier island and coastal lagoon with feature typical of mapping and monitoring amenable to sUAS approaches; (a) oceanfront shoreline and beach-dune habitats; (b) inlet channels and flood and ebb tidal deltas; (c) relic ridges and hammock islands; (d) lagoon subtidal bathymetry and benthic habitats (SAV, oyster and clam beds, soft-bottom flats); (e) marsh islands and platform marshes; (f) river channels and fresh-tidal mixing zones; (g) shoreline structures; and (h) estuarine beaches.*

## 2. Estuarine shoreline change data sources

A growing variety of geospatial data allow for the mapping, monitoring, and change analysis of estuarine shorelines. These data include historic nautical charts, topographic maps, and aerial photography that cover extensive areas of the estuarine landscape. The advent of aerial photography in the United States in the 1930s and 1940s ushered in routine surveys of agricultural landscapes for crop inventorying and land management. These data can be georeferenced, although rural estuarine areas may lack adequate, consistent ground control points to quantify spatial accuracy. Similarly, historic manuscript maps and nautical charts predate precision Global Positioning System (GPS)/GNSS positioning, yet where ground control and persistent landmarks are available, can provide useful georeferenced data. The National Oceanic and Atmospheric Administration's (NOAA) Historic Aerial Photographs, historical shorelines, and digitized nautical chart archive are useful resources. In the United States, the United States Geological Survey (USGS) topographic quadrangle maps provide sufficient accuracy and a degree of shoreline characterization (developed, forested, or marshes). The US Department of Agriculture's National Aerial Photography Program (NAPP) has long provided annual aerial photographs for crop inventory purposes. Some of these data include color-infrared (CIR) images and georeferencing sufficient to quantify spatial accuracy. However, most of these aerial photography programs do not specifically acquire imagery at tide-coordinate times. This may alter or bias results in shoreline mapping of shallow slope gradients, where horizontal position of the shoreline is greatly affected by the tide stage. The same phenomena may also affect nontidal shoreline mapping that fluctuates as a result of river stage or wind tides.

An array of baseline geospatial data provide for the analysis of estuarine shorelines and their historical contexts. In the United States, these data have included orthomosaic aerial photography, sometimes also supplemented with projects to georeference older historical aerial photos where possible and extend the longitudinal timeframe covered. Since estuarine shoreline change rates are typically much smaller than higher-energy oceanic shorelines and beaches, a longer time horizon is beneficial to capture change, so long as geospatial data are rigorously georeferenced (a severe challenge in rapidly changing areas or those without fixed and stable reference features). However, newer frequency of aerial data, Light Detection and Ranging (LiDAR) mapping campaigns, and ultra-fine-scale satellite imagery have vastly improved the spatial resolution of potential shoreline mapping, such that these newer high-resolution data can capture dynamics that may be impossible to measure robustly with historic data sources. Nonetheless, some limitations linger with these newer sources, such as expense of flight operations, data volume, processing costs, dependency on weather-restrictive flight operations, and availability of satellite or airborne sensor platforms (orbital characteristics and frequency or temporal resolution). Smallsats such as Planet, Maxar Technologies, and Capella Space that are newly available may not capture large areas at the needed time, particularly with regard to tidal stage. This can severely complicate shoreline change analysis when images are acquired at different tidal stages or during periods affected by wind tides, storm surges, or seiching. Acquiring imagery at varying tide stages and water levels can become a significant source of uncertainty and error that can propagate through time-series measurements of shoreline position. Newly available small Uncrewed Aerial Vehicles (sUAV) platforms allow for flexibility and increasingly resilient use and operation in challenging weather conditions. At least for relatively local, subregional studies, sUAV mapping can take advantage of small windows of favorable weather and can allow for more systematic and accurate mapping of desired tidal stage, which in turn can improve the systematic consistency of observations and reduce shoreline change analysis inherent error and positional uncertainties.

Although access to data sources can be considered to have broadly increased in recent years, substantial hurdles still exist in quality,

spatial range, temporal consistency, and resolution both nationally and within states. For instance, [15] compared the amount of hardened shoreline in the United States to that of a previous national-level study [16] and found that data discrepancies and availability issues prevent the calculation of annual rates of shoreline hardening, and US states and federal agencies consistently fail to collect data. Specifically, data discrepancies included expanded mapping range, changes in map resolution, and the coastline paradox. The coastline paradox [17] states that shoreline length is a fractal dimension, such that the length increases as the resolution of the data increases and decreases as the resolution decreases.

To date, only 15 coastal states have calculated shoreline change rates, with 9 mapping their entire coastline and 6 mapping selection segments of shoreline (see **Table 1** in [15]). Critically, only nine states maintain monitoring programs that regularly

| Shoreline movement metric | Calculation |
|---|---|
| Net shoreline movement (NSM) | Distance (m) between oldest and most recent shorelines |
| End point rate (EPR) | NSM/time (years) between oldest and most recent shorelines |
| Shoreline change envelope (SCE) | Maximum distance (m) between all shorelines |
| Linear regression rate (LRR) | Rate of shoreline change is determined by fitting a least-squares regress line to all shoreline points for a given transect |
| Weighted linear regression rate (WLR) | Rate of shoreline change with greater emphasis on more reliable shoreline data to determine a best-fit line. Weighting, $w$, is a function of the variance in uncertainty $e$ of the shoreline position measured $(w = 1/e^2)$ |

**Table 1.**
*Shoreline movement metrics [18, 19].*

update shoreline change. Frequently, states rely on national data such as the United States Geological Survey's (USGS) National Assessment of Shoreline Change (NASC), the NOAA National Shoreline, NOAA Continually Updated Shoreline Product (CUSP), and National Oceanic and Atmospheric Administration's (NOAA) Office of Response and Restoration (OR&R) Environmental Sensitivity Index (ESI). Each of these datasets leverages different methodologies for calculating shoreline location, has different resolutions, and different rates of updating that can increase the risk of error and interpretation between various sources [15].

## 3. Shoreline change analysis techniques

Having shoreline data from remote sensing provides for a variety of potential analyses, yet the accuracy and precision of shoreline change measurements depend on the quality of shoreline position mapping and the variability of shoreline changes [20]. Vector-based shoreline digitization and change analysis using transects, profiles, or line-intercept techniques largely derive from traditional cross-shore surveys that extend from a dune, across a beach, and to the shoreline or a predetermined depth or feature offshore. Geospatial techniques have replicated this in a variety of software, such as the US Geological Survey's Digital Shoreline Analysis System (DSAS) [18, 19], which establishes baselines, casts transects, and measures incremental shoreline position changes similar to historic beach transect field approaches. As data accumulates and uncertainties are better quantified and reduced in observations, potential improvements can be gained in future projections. DSAS is freely available software that works within ESRI's desktop Geographic Information System (ArcGIS ArcMap). Various techniques are available (**Table 1**) to estimate shoreline change rates using DSAS, such as net shoreline movement (NSM), shoreline change envelope (SCE), end point rate (EPR), linear regression rate (LRR), and weighted linear regression (WLR) [19]. Shoreline changes are measured as mentioned in **Table 1**.

As an example, the LRR shoreline change rate as a regression equation takes the form LRR ($y = mX + b + e$), which is functionally calculated per equation (1), where slope $m$ is the rate of change (distance over any given shoreline year), $b$ is the intercept (distance of given year shoreline from baseline) and $e$ is error, all taking the form:

$$LRR = slope^{*}\ shoreline\ date\left(years\right) - distance\ from\ baseline \quad (1)$$

Extrapolation of a chosen rate change allows for estimation of a future shoreline position (e.g., 10 or 20 years in the future), with the possible use of an error and uncertainty envelope that incorporates each shoreline's estimated positional error. Error estimates that combine field-based and remotely sensed shorelines with variable positional accuracy and digitizing error are thus able to be accounted for in future uncertainties (e.g., [21]). Such future shoreline positions inherently invoke several assumptions as to future sediment supply, wave erosion, and landward morphology and management, but these can be useful as first-order estimates and are analogous to other risk assessments on ocean shorelines [22] and coastal management policies such as setbacks [23].

Another example of spatial analysis of estuarine shorelines and data science approaches is the Analyzing Moving Boundaries Using R package (AMBuR) [24, 25]. AMBuR has options to handle complexly curved shorelines often found in estuaries, such as marsh shorelines, pocket beaches, and backbarrier and spit embayments. Regardless of which spatial analytical technique is applied, future sea-level, flooding, and storms must be assessed as having potential nonlinear and morphodynamic feedbacks, such that past erosion rates may not be easily projected in the future. As costly LiDAR DEMs become dated, their elevations must be adjusted to real shore vertical land motion (VLM) or coastal subsidence, or the data must be reacquired. In this case, UAVs provide a valuable, fine-scale option for accurately mapping coastal elevations.

While the above geospatial techniques are robust and becoming widely adopted in estuarine shoreline analysis, other opportunities and challenges exist. Besides digitizing shorelines from UAV aerial orthoimagery, Digital Surface Models (DSMs) may be derived as a 3D source for automated shoreline extraction. For instance, a DSM derived by Structure from Motion (SfM) algorithms from stereoimage photogrammetry can be transformed into a desired geodetic datum or local tidal datum and subsequent shorelines extracted by contouring and interpolation. Laser scanning technology, traditionally from terrestrial tripod-mounted systems, is also sufficiently miniaturized now to allow their use as payload on sUAV. One of the remaining challenges in estuaries, however, is the separate tasking of topographic and bathymetric mapping and the remaining complexity, cost, and logistical constraints of combined topobathymetric mapping. Very often, one or the other topographic and bathymetric mapping are separately run missions and sensors. Oftentimes, shoreline changes do not contain any bathymetric data to inform managers of potential feedback such as offshore erosion, bar formation, or transport. DSAS' future shoreline projection incorporates estimated uncertainties but does not incorporate direct topographic or bathymetric data. Regardless of approach, it is also advisable to assess the positional and vertical accuracy of the resulting DSM and account for elevation uncertainty [26]. Hence, several areas of research remain for technical integration and modeling of topobathymetric data and future 3D shoreline prediction.

## 4. Emerging autonomous systems for Estuarine shorelines

A wide variety of platforms and sensors are in use and emerging for estuarine environmental analysis and monitoring. The selection of platforms is complex and mission-driven, usually depending upon resolution requirements, areal extent and feasibility, payload weight, and air and seaspace operating conditions and regulations. Altitude affects imaging and the ground sample resolution and is limited by the airframe design and propulsion capabilities. The need for orthoimagery versus also 3D photogrammetry and Structure from Motion (SfM) analyses affects the mission duration and flight time, which affects areal extent and distance from line-of-sight (LOS) and quantity of data collection. Fixed-wing and Vertical Takeoff and Landing (VTOL) design small UAS carry advantages for imaging large areas given typically longer flight times per mission. However, these may also be limited by payload weight, whereas larger hexacopters and quadcopters can be scaled to carry payloads in excess of 4–5 kg. Relatively heavy sensors such as multispectral dual-camera systems and topobathymetric LiDAR may require the largest capacity payloads and more remain in the arena of piloted platforms. Wind speed and gustiness also affect the platforms differentially. Typically a fixed-wing can fly in higher winds for longer periods, albeit limited by safety in low altitude and takeoff landing. Quadcopters with immovable rotors will require additional battery swaps when operated at the upper end of their intended wind velocity ranges. Similarly, the operation of Autonomous Surface Vessels (sASV).

A conceptual model is presented in **Figure 2** of a selected array of small uncrewed autonomous systems (sUAS, referring broadly to both aerial and aquatic) platforms operating in estuaries. All platforms share a common requirement of an operator or remote pilot for mission planning, ground control, observing safety, and ensuring GPS/GNSS and telecommunications, battery, and data management. sUAS include quad-, hexa-, and octocopters capable of carrying digital SLR and video cameras, laser range-finders, and scanning LiDARs. sUAS may also be configured with multiple sensors and also can carry sampling devices for remote collection of water samples for later laboratory measurement (e.g., water quality monitoring such as fecal coliform and harmful algal bloom detection and classification). In situ sensors are also often part of the collection systems, such as water level, tide gauge, or flood sensors. Capturing shoreline data, depth, or other temporally varying phenomena from sUAS will often require the accurate measurement of tidal stage and, over time, the correction or adjustment. As a form of Internet-of-Things (IoT) technology, in situ sensors are also increasingly ubiquitous and connected systems and may serve as benchmarks, GPS base stations, or communication relays (e.g., WiFi or cellular networks) for sUAS platforms. A variety of

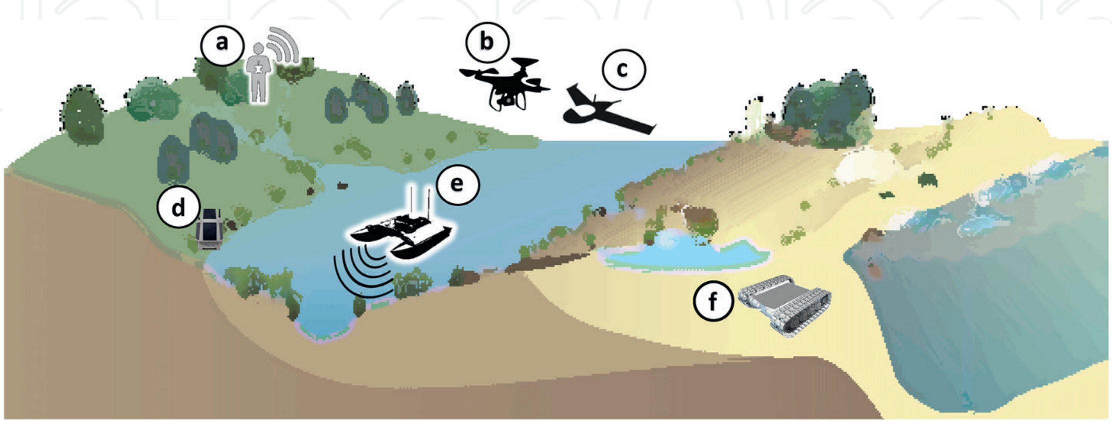


**Figure 2.**
*Conceptual diagram of a selected variety of sUAS systems for estuaries, including (a) operator/remote pilot and associated mission planning and GNSS base and communications control; (b) quad-, hexa-, octocopter sUAS platforms; (c) fixed-wing sUAS platforms; (d) in situ fixed sensors such as water level, flood, or water quality sensors and GNSS base stations; (e) autonomous and remote surface vessels and sensors; and (f) autonomous or remote crawler for terrestrial and benthic survey.*

small Autonomous Surface Vessels (sASVs) are also increasingly common and capable of modular, multipurpose, multisensor data collection. As an example, the catamaran-style platform hydrone ASV developed by Seafloor Systems [27] focuses on echosounding for shallow-water bathymetry mapping. Such systems are also highly modifiable, with payloads up to 35 kg (see later case study) and capacity enough for various sounders and aquatic samplers. Hydrone ASV can be modified to add gimbal-mounted camera systems, vessel Automated Identification Systems (AIS), and a host of water quality sensors and other sounders (e.g., dual frequency, sidescan, or multibeam sonars) provided onboard battery systems, floatation, and communications are adequate. Lastly, there are also remote and autonomous crawlers, such as C2 Innovations' amphibious estuarine robotic crawlers (the *Sea Otter*, *Sea Ox*, *Mudskipper,* and *Drifter* [28]). Such systems are uniquely capable of autonomously sampling benthic sediments and coring.

### 4.1 Small uncrewed aerial vehicles (sUAVs)

Numerous studies have shown promise in the use of drones and drone sensor-derived products for the monitoring of site-specific topographic change and ecological impacts. UAVs and an increasing variety of miniaturized sensor payloads are proving useful for a host of coastal environmental research including shoreline monitoring, wetland delineation and mapping, flood detection, and even nearshore LiDAR bathymetry [29]. Measurements derived from drone-acquired imagery processed with photogrammetric tools have been found to be comparable to other traditional measurement techniques in their ability to provide accurate and reliable estimates of human-related environmental impacts on vegetated, for coastal dune management, and other natural environments [30, 31]. The generally high and highly user-configurable spatial and temporal resolution of UAV image sensor data, coupled with the ability to acquire human subjects' data remotely, makes the use of drones an extremely attractive data collection mechanism.

Multiple studies of the application of UAV methods to coastal research have affirmed that small autonomous aerial systems are particularly useful for investigating the shape, orientation, and morphology of the shoreline, beach, and bordering dunes and wetlands. One coastal erosion study reported that modeling and 3D analysis using existing digital elevation data, RTK GPS surveys, UAV imagery collection, and photogrammetry resulted in the development of digital surface models (DSMs) with vertical accuracy better than 10 cm [32]. Another study examining the utility of UAV imaging for detecting and cataloging shoreline and beach change confirmed that inexpensive commercial UAVs can be used to detect topographical changes, estimate volumes, and produce maps rapidly and economically [33]. Furthermore, the use of UAVs to examine coastal landscape morphodynamics beyond two-dimensions and to quantify the three-dimensional response of beaches to storm events, sea-level rise, and other stressors was found to be "essential" to understanding future coastal vulnerability [34]. Nonetheless, [33] underscores the ability to develop precise, repeatable, automated UAV flight plans to provide insight into coastal dune and landscape evolution by recording large morphodynamic processes at high and user-specified temporal resolution.

sUAV platforms operable in estuaries have also evolved and diversified themselves. Balloon and kite aerial photography operated by tethers and a pilot were pioneering in this respect. Once more autonomous navigation and reliable control systems and onboard processing became miniaturized, quadcopters and then larger hexacopter and octocopter rotary propulsion systems emerged. Fixed-wing UAVs such as the eBEE [35] were shown to have utility in longer flight times and mapping extensive shorelines such as barrier islands. Recently, Vertical Takeoff and Landing (VTOL) platforms such as the Wingtra developed with similar advantages and capacity to carry modular payloads, farther, and longer. The FIXAR007 fixed-wing VTOL [36], in comparison, uses canted fixed rotors for both vertical takeoff and horizontal flight. Thus, the variety of UAV platforms present tradeoffs in advantages and disadvantages as to payload, endurance, complexity of mission operation, and piloting. Power sources, line-of-sight distance, and mission duration and extent continue to largely dictate selected platforms and payloads, and in many situations, multiple platforms of UAV or combined with ASV are required.

While end-users are presented with many options among platforms and payloads, advances in remote sensing technology generate rapid, nondestructive methods for siting, executing, and monitoring coastal ecosystems. By providing on-demand access and remote sensing capabilities, greater resolution than sensors from satellites and occupied aircraft, and the ability to cover large areas quickly, can be surveyed more frequently at a more cost-effective rate, sUASs are opening up new possibilities for siting, executing, and monitoring efforts. sUASs have increasing potential to reduce the costs associated with restoration efforts, making site assessment and long-term, broad-scale monitoring more achievable [37]. The diverse range of platforms and payloads available, such as high-resolution, multispectral imaging, structure from motion photogrammetric processing, and water quality monitoring, is giving conservation practitioners the tools they need to properly plan, execute, and evaluate these projects [37].

Regardless of which UAV platform is selected for a mission, coastal estuarine operations still must consider common factors. Controlled airspace in some estuaries and environmental conditions (waves, tides, and traffic in the Bay) are critical limitations. In Hampton Roads, Virginia, USA, the third largest port is also home to over a dozen military installations and Norfolk Naval Station, the largest navy base in the world. Hence, flight and estuarine operations alike within this seaport are complex and sometimes and places very highly restricted. The inherent variation of tides in some estuaries requires careful mission planning, especially for mapping bathymetry and shoreline positions. Operations also need to account for potential latency or noncurrency in mission planning software. Oftentimes GoogleMaps, Streetview, and OpenStreetMaps and proprietary imagery with unclear date and currency are used in mission planning, yet docks, vessel traffic, and hydrographic conditions may have changed between the image date and mission date, leading to potential risk or error. In addition, ephemeral features may pose hazards in estuaries to UAV or ASV operations, including migratory waterfowl, avian predators such as eagles, hawks, and ospreys (known to attack UAVs), wrack and floating marine debris as well as crab pots and ghost fishing gear potentially fowling ASV propulsion. Relict powerlines or poles, trees, and hidden docks and hazards to navigation may abound in study areas, so it is critical that sUAS pilots and mission planning take a holistic approach to operations.

### 4.2 Small autonomous surface vessels (sASVs)

The emergence of UAV applications has reached a relatively mature and operable state of technology in coastal estuaries, yet the value of subtidal hydrographic mapping and surface imaging, and data collection are also rapidly advancing. Small Autonomous Surface Vessels (sASVs) have the potential to capture bathymetric data to augment UAV topographic data and produce seamless "topobathy" surfaces. A variety of ASV platforms on the market have focused on bathymetric mapping or benthic habitats, including Seafloor Systems' *Hydrone* and *Echoboat* series, Biosonics' hydroacoustic sounders, and Blue Robotics (a provider of Remote Operated Vessel electronics, ROV). A substantial open-source and Do-It-Yourself (DIY) hobbyist sector has also advanced ASV-related systems such as PixHawk controllers, HERE GPS, and MavLink navigation and transceiver systems. Ease of deployment and modular payloads are a hallmark of many small ASVs, such as Michigan Tech University's *BathyBoat* [38]. The *BathyBoat* is able to reach restricted areas such as harbors, navigate under low bridges, deploy from shore, ship or helicopter, and to carry diverse sensors with real-time remote display on laptop or tablet.

Developing literature on sASV systems has also emerged to a level of operational state. Hurdles of academic program developments around autonomous maritime vehicles while also outlining examples of low-cost open-source designs for platforms that can be readily implemented [39]. A prototype multipurpose platform, the AG-0, includes design data and 3D models and a detailed description of controllers (PixHawk, Raspberry Pi, and Arduino). Various sensor packages informed by environmental scientists focused on water quality. ASVs have been deployed for marine debris removal and algal bloom mapping and removal [40]. A custom water environmental mobile observer (WeMo) with a focus on water quality measurement has also been developed to include dissolved oxygen, which is critical to estuarine ecosystem health [41]. Low-cost, efficient, and accessible ease of use were prioritized for WeMo's design in anticipation of its use by citizen scientists and other nonspecialist users. The ReefRover USV [42], a small platform focused on stereo imaging of coral reefs, focuses on SfM-derived 3D models of coral reefs for benthic habitat classification and mapping. Such multidimensional data enhances capabilities of biodiversity monitoring, coral health such as bleaching, pollution, or reef recovery from damage, and reef erosion or accretion and sediment dynamics.

Besides tropical coral environments, high wave energy surf zones that are often difficult for hydrographic surveys have attracted ASV mapping capabilities. A low-cost USV for surf zone bathymetry surveys, with the novel use of a jet drive to mitigate propeller damage and a closed deck bubble to ensure the vessel automatically rights itself in case of capsizing in surf has been developed [43]. Similarly, a small USV was developed for advanced maneuverability and shallow water surveying performance in Korea [44], using the Wave Adaptive Modular Vessel (WAM-V) catamaran platform. The WAM-V deployed a multibeam echosounder and tested the maneuverability requirements of multibeam surveying needs for swath coverage in shallow waters. Indeed, ultra-shallow areas may be inaccessible and even impossible to operate traditional piloted hydrographic survey vessels, providing a niche for specialized sASV and autonomous techniques [45]. Shallow waters, generally, are a suitable frontier for ASV applications. Combining real-time kinematic (RTK) GNSS and USVs for repeated bathymetric surveys and change analysis, time-series changes in the Neuse River of North Carolina have been observed to assess coastal bluff erosion [46].

Ultra-shallow waters in estuaries present a special challenge to bathymetric surveying, sometimes requiring the use of multiple surveying methods and instruments and spatial interpolation to produce seamless digital bathymetric models (DBMs) [47]. In addition, the shallow depths may produce reverberations that are indistinguishable from the bottom at ultra-low depths, and systems that employ swath scanning in shallow waters inherently cover less area of the bottom than in deeper waters, requiring longer and more intricate survey tracks and time to complete. Bathymetric surveys by ASV are also nontrivial with respect to spatial analysis and interpolation, requiring careful consideration of the accuracy required and uncertainty, knowledge of applicable software and algorithms for interpolation, and technical evaluation of shallow water and seamlessness with shoreline and topographic data. However, ASV surveys may still be superior to topobathymetric LiDAR where conditions are especially turbid, airspace is highly regulated, and/or weather conditions restrict UAV and airborne LiDAR acquisition. Where depths are constrained for even ASV surveys, new Gaussian Process (GP) algorithms can be implemented to constrain survey missions with bounding polygons and create efficient tracks [48]. Certainly, environmental limitations of ASV operations have been greatly overcome by technological advances, and small ASV platforms are increasingly being deployed in estuaries for a variety of scientific and applied purposes.

## 5. Case studies in estuarine shoreline change

Having examined the imperative scientific and practical applications of sUAS technologies in estuaries and their technological variety, this section describes a few representative case studies drawn from estuaries of the Mid-Atlantic United States. The large Chesapeake Bay and the adjoining Albemarle-Pamlico Estuarine System (APES) provide a multitude of diverse problems for scientific and management applications. The region is undergoing rapid sea-level rise with variability owing to differential coastal subsidence. Coastal storm tracks from nor'eastern extratropical cyclones and tropical storms provide short-term disturbances and shoreline changes. A strong contrast in coastal urban seaports, recreation, and rural development also exist across the region. Some coastal lagoons are highly flushed and connected to the ocean via inlets, whereas some of the larger "sounds" of the APES in North Carolina are much less often circulated and often oligotrophic and stratified. The region also features a biogeographic latitudinal gradient in ecosystems and climate, although much of the region is also low-lying coastal plains.

### 5.1 Urban tidal creek inventory and change analysis (Norfolk, Virginia, U.S.A.)

A historic tidal creek and working waterfront, dredging and filling, this case study is representative of urban waterfront restoration and eco-development. The nonprofit Elizabeth River Project is developing a Ryan Resilience Lab on Knitting Mill Creek, a tributary to the Lafayette River in Norfolk, Virginia. To develop a baseline and historic context for future monitoring, a site survey by DJI Mavic quadcopter was conducted. The mission also flew 3D cross-hatched flights and high-onlapping images for DSM development. In addition, a hydrone ASV was deployed to collect preconstruction bathymetry. Derived DSM and DBM were subsequently each transformed to a common MHHW tidal datum for subsequent resampling and interpolation to a seamless topobathymetry model. **Figure 3** shows the series of representative products, including an overlaid parcel plat map (a), tide gauge on-site used to normalize the time-series bathymetry survey points (b), seamless orthoimage from UAV in 3c, and the final topobathymetric surface (d). The success of these collections led to an ongoing effort to image the progress of the construction and final site development to include living shorelines and experimental marsh restoration. In addition, the bathymetry data has been useful to update a hydrodynamic model grid (DELFT 3D) to experimentally assess the effect of using high-resolution bathymetry for flood modeling.

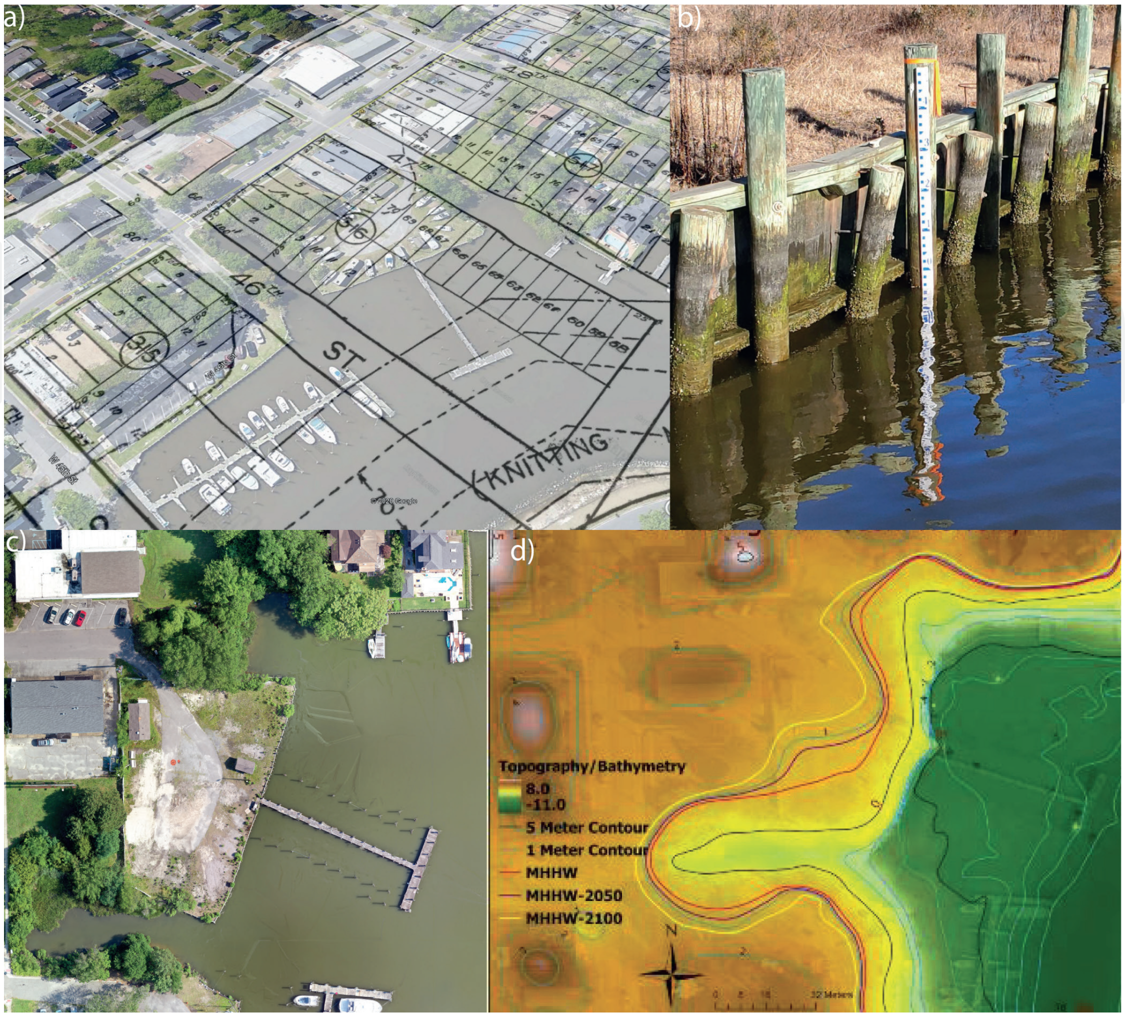


**Figure 3.**
*Urban estuary shoreline change and topobathymetric model for knitting Mill Creek, Norfolk, Virginia, U.S.A. showing (a) historic plat development and working waterfront with the dredged creek channel; (b) present bulkheaded shoreline with tide gauge; (c) sUAS orthoimage mosaic prior to site redevelopment; and (d) digital topobathymetric model.*

## 5.2 Shoreline change and estuarine beach dynamics

An historic estuarine beach town, the Town of Colonial Beach, Virginia, is situated on the tidal mainstem of Potomac River, astride the Maryland-Virginia border approximately 80 km south of Washington, D.C. The town's public beaches on the river are historically popular and relatively rare around the Chesapeake Bay, yet they have experienced severe erosion and potential volume loss since Hurricanes Irene (2011) and Sandy (2012), as well as repeated major nor'easters extratropical cyclones. Post-Sandy topobathy LiDAR was collected at an opportune time in a large campaign for the region, but the area lacked publicly available current bathymetry and only selectively available topographic LiDAR. Hence, to better assess the trends in shoreline changes *and* volumetric offshore and on-offshore and alongshore sediment dynamics, a joint UAV and Hydrone ASV survey project was devised. The town and its local resilience partners sought to inform future plans for the beach and their adaptation. A seamless topobathy DEM and shoreline change analysis were developed, using primarily historic shorelines from aerial photography, 2012 topobathy LiDAR, and new missions using a DJI Mavic 2 pro-UAV and

Hydrone ASV. Future coastal compartment assessment to evaluate long-term long-shore drift, sedimentation into Monroe Bay and marine channel navigation and restoration. The mission plans for the UAV and ASV are presented in **Figure 4**, including (a) the North Beach study area and adjoining public beach, (b) DSAS baseline, transects, and historic shorelines, and (c) Hydrone bathymetry survey, including nested scales of tracks using the single-beam Blue Robotics echosounder operating at 2 Hz. Hydrone bathymetry was collected simultaneously with UAV acquisition, and depth points were later tidal-corrected after 2 hour mission using the nearby tide gauge at Dahlgren (station 8,635,027).

Results of the shoreline change rate analyses at Colonial Beach are depicted in **Figure 5**, including SCR rates using DSAS (a), DEM of difference for the topographic LiDAR and UAV DSM (b), and the DBM of difference for the hydrone ASV survey and the 2012 Bathy LiDAR DBM in 5c. Insights from these analyses were provided to the town to inform their ongoing desire for soft stabilization and preserving safe public use and access to North Beach. Additionally, the analysis quantified the volumetric loss of erosion of the beach and contemporaneous loss of volume offshore. Fine-scale features indicating scour around stormwater outfalls and riprap were also found, as well as net erosion around some of the hard stabilization breakwaters to the south. The study prompts the further analysis of other beaches in the area and the long-term prognosis of net erosion, absent new or increased sediment supply, and the potential portability of techniques to other towns with estuarine beaches around the Chesapeake Bay (e.g., Cape Charles, Buckroe Beach, and the lower James River).

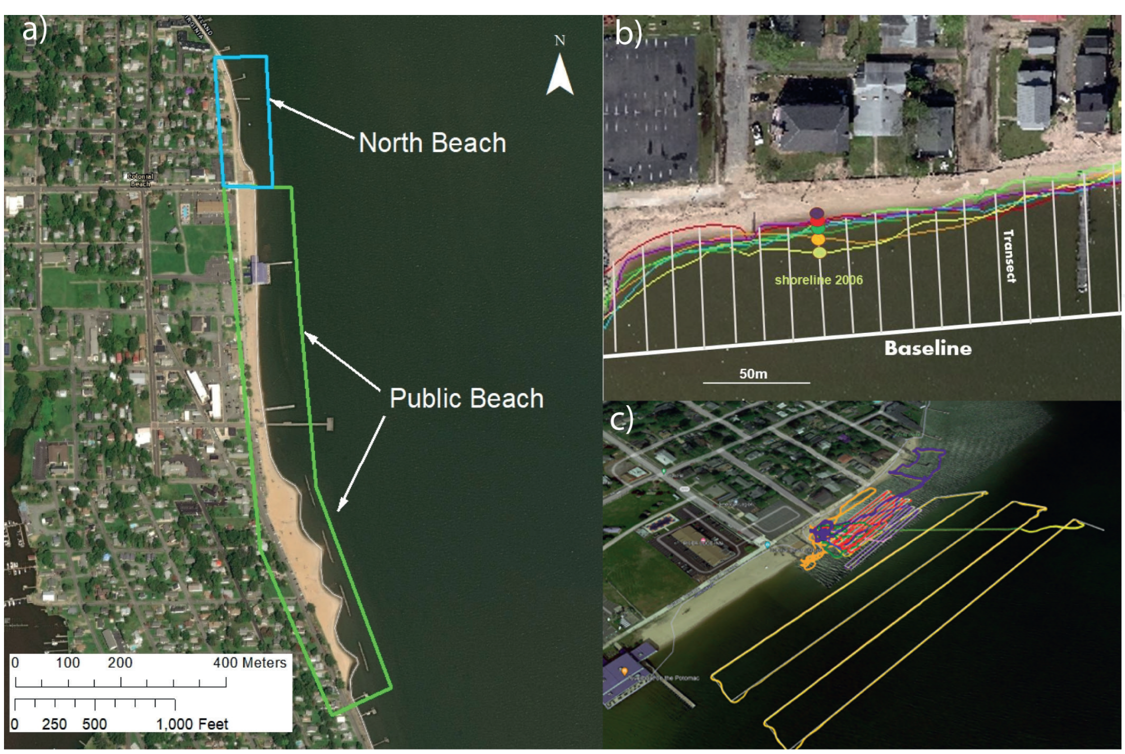


**Figure 4.**
*Case study area, town of Colonial Beach, Virginia, U.S.a. showing (a) the location of the town's North Beach and public beach areas covered by sUAS orthoimage acquisition; (b) digitized shorelines from multidate imagery and DSAS software baseline and transects for change analysis; and (c) tracks of the hydrone ASV bathymetric survey mission at North Beach.*

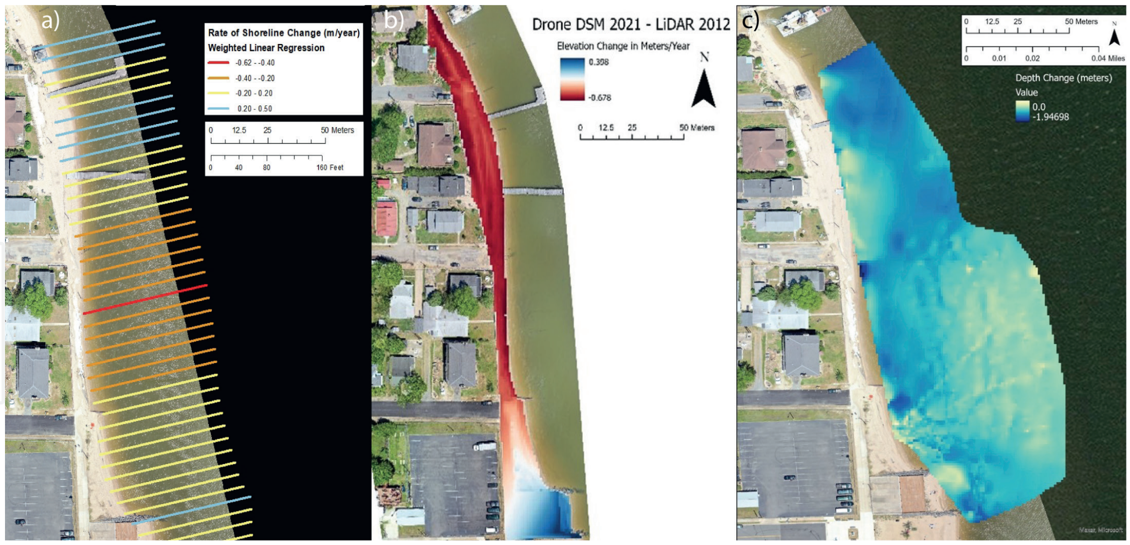


**Figure 5.**
*Shoreline changes at the town of Colonial Beach mapped by (a) shoreline change transects using USGS DSAS; (b) volumetric DEM of difference between LiDAR DEM and sUAS DEM; and (c) topobathy LiDAR and hydrone ASV bathymetric change (DBM of difference).*

### 5.3 Experimental living shoreline design and restoration

Novel approaches to NNB management include living shorelines, which have grown in popularity for erosion management, habitat conservation, and promotion of ecological co-benefits around the Chesapeake Bay. Another challenge being addressed in the region is the maintenance of navigation channels and the provisioning of public waterway access. In an experimental project, the Virginia Sea Grant Consortium, private company Biogenics, and partner universities are working to assess the beneficial reuse of dredged channel sediments in biologs tubes for a living shoreline on a nonnatural tidal creek. Whitaker Creek lies in the low-lying watershed tributary of the Severn River in Virginia, in the lower Chesapeake Bay, and near the mouth of York River and Mobjack Bay. sUAS, in this case, provides a key, current baseline condition assessment prior to developing a public access boat ramp, channel dredging, and the experimental biotube and marsh restoration. In addition, the hydrone ASV will be tasked with bathymetric mapping and change analysis. sUAS will monitor the reconstructed marsh health and 3D morphology over time before, immediately after restoration, and over one or more years after the project. Historic shorelines from airborne imagery and current UAV imagery will allow DSAS shoreline change rates to be derived. Hydrone ASV bathymetry will collect baseline bathymetry and intertidal sediment volume and channel depth for dredging and biologs. Shown in **Figure 6**, Whitaker Creek is a few hundred meters long and approximately 10 m average width, with a small turning basin near a boat ramp and adjoining marsh flats that have seen historic disturbance by development and channel alteration or ditching. **Figure 6a** shows the inset of 6b, where a steep but narrow creekbank is evident at low tide on February 25, 2023. This example illustrates the challenge to UAV mapping, wherein the DSM of low but steep slope will necessitate low-level flying and capture of low oblique imagery for photogrammetric use of SfM and a 3D model. An alternative to this approach is UAV LiDAR or LiDAR or SfM from photogrammetry from the hydrone ASV taken at creek level horizontally. Given the ongoing erosion and incision

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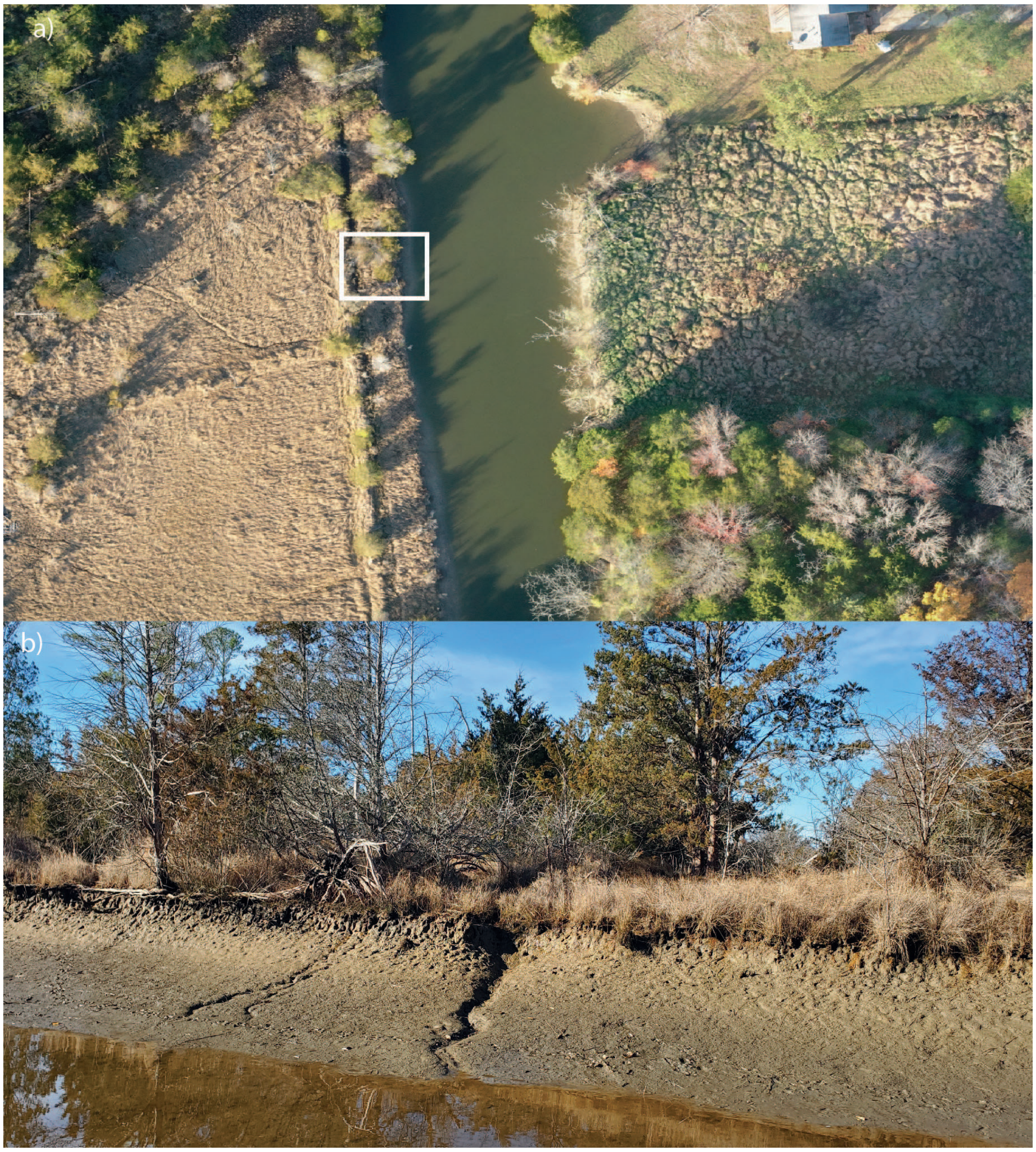


**Figure 6.**
*Challenges of micro-relief capture and characterization. Whittaker Creek is the site of a living shoreline restoration along a dredge tidal creek channel in the Severn River tributary to the Chesapeake Bay in Virginia. The UAV orthoimagery (a) is limited to 2D and continuously varying tidal and shoreline position, whereas the creekbanks (b) are steep and prone to fine-scale erosion and a subtidal channel that is highly turbid, requiring acoustic bathymetric survey by ASV.*

of the creekbank, this example illustrates the versatility of platforms and sensors that can be used to develop the 3D model and monitor the progress and results of the project over time.

### 5.4 Natural area monitoring

A related case study is presented here from the New Point Comfort (NPC) Natural Area Preserve, located on the western side of the Chesapeake Bay, approximately 40 km northwest of the mouth of the Bay and the Atlantic Ocean. The h2ha preserve comprises maritime forests, windswept dunes, and low- and high-marsh wetlands on a spit between Mobjack Bay and the Chesapeake Bay. Relatively isolated from coastal land use development, this area provides critical habitat for migrating waterfowl and protection for several federally threatened species.

Anecdotal reports of dynamic shoreline erosion and habitat loss owing from repetitive storms and flooding events prompted investigation and confirmatory analysis. New Point Comfort's remote location and difficult access made it well-suited for UAV image acquisition, monitoring, and testing the development use case of derivative products such as shorelines, habitats, and landforms. Accordingly, a long-term UAV image acquisition and monitoring plan was developed to establish baseline shorelines, elevations, and topography for the preserve and subsequently acquire poststorm imagery. This plan outlines the development of a high-resolution time-series archive of tidally coordinated UAV-acquired digital shoreline data that will improve monitoring and understanding of geomorphological trends at this vulnerable site and allow for change detection and geospatial (GIS) comparative analysis. UAV orthoimagery with visible spectral bands is also capable of mapping salt marsh zonation reliably, exceeding the available federal National Wetland Inventory (NWI) thematic detail (interpreted from aerial photographs using a hierarchical classification scheme) and the spatial resolution of Landsat (30 m and typical for synoptic regional land use/land cover classes that also do not differentiate marsh zones).

Small quadcopter UAVs (e.g., DJI Mavic 2 Pro) were employed to collect 3-band aerial imagery of the study area comprising the western-facing beaches and wetlands of the NPC Preserve extending north to south approximately 1.25 km from a narrow observation deck that served as a takeoff and landing zone, to the southern tip of the peninsula at the intersection of Mobjack and Chesapeake Bay. For each flight, a minimum crew of two, a Remote Pilot in Charge (RPIC) and Visual Observer (VO) was used to ensure safe and efficient mission execution. As these flights occur in unrestricted airspace at or below altitudes of 400 ft. (122 m) above ground level (AGL) and in accordance with Federal Aviation Administration (FAA) rules, no special permissions or preauthorizations are required.

The baseline and all future aerial surveys of NPC were planned to cover the entirety of the sandy beach/shore to include portions of adjacent wetlands, maritime forest, built infrastructure, and waterways. A grid flight pattern was flown to optimize image collection for the development of high-resolution orthophoto mosaics and 3D digital surface models (DSMs). Flights were also planned to minimize impacts of wave action, any increased riverine flow (from upstream rainfall or snow), and other conditions that may elevate the water level above the observed tide. To capture the maximum amount of preserve topography, flights were tidally coordinated with the nearest NOAA tide gauge (Mobjack Bay, station ID 86371999) for imagery to be acquired as close to low tide as possible. After each flight, Geographic Information Systems (GIS) was used to analyze the UAV-acquired imagery and to digitize shoreline and marsh positions as preerosion reference conditions.

Following initial UAV collection and development of baseline condition data for NPC, the study sites will be monitored for exposure to storm activity with erosional potential for a minimum of four future storm events. As soon as practicable after storm events, another round of tidally coordinated image acquisition flights will be conducted at the study location. GIS analysis will again be employed to delineate the shoreline position and identify geomorphological change. Image-derived GIS data products will highlight the poststorm 2- and 3-dimensional position and landform characteristics, thereby providing for change analysis with prior UAV-derived data as

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well as historic maps, nautical charts, aerial photography, and topographic LiDAR. Where necessary, UAV mapping will employ temporary targets placed on the ground and mapped with RTK GPS and opportunistic GPS points along key features as ground control points (dune crest, toe, shoreline, scarps, and other images identifiable and stable features as may be found). The NPC site is shown in **Figure 7a-c** depicting the general area in the oblique UAV photograph (a), a mosaic orthoimage

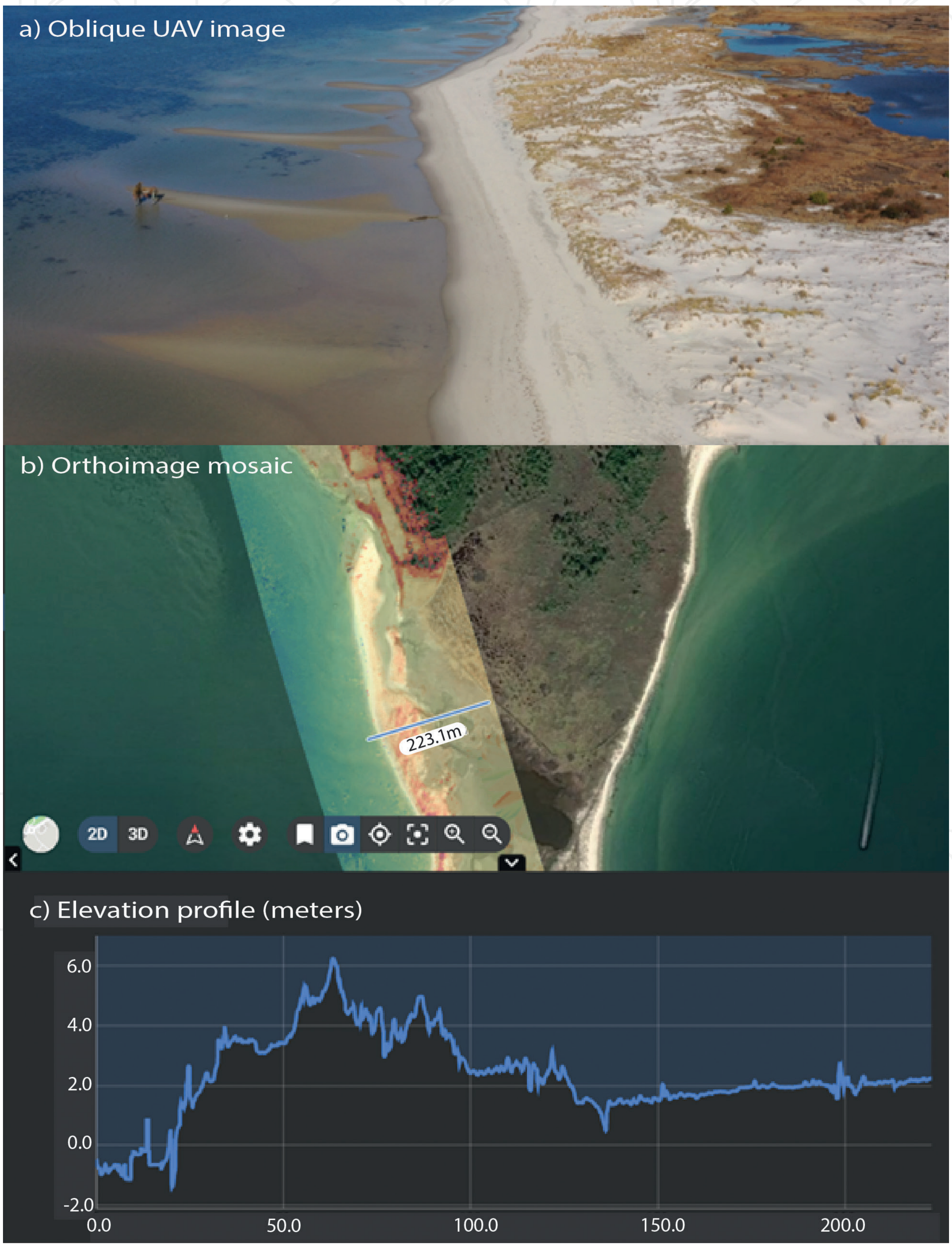


**Figure 7.**
*Shoreline habitat conservation example from new point comfort natural area preserve, Chesapeake Bay, Virginia, showing (a) oblique UAV photograph of subtidal bars, beach face and cusps, incipient foredune, and back dune swale shrub-scrub habitats; (b) orthoimage mosaic and transect; and (c) elevation profile along the transect.*

(b) including a transect of the UAV 3D output from SfM analysis, and (c) highlighting a topographic profile of the transect, illustrating elevation changes corresponding with landform and vegetation types. Such data will enable monitoring the habitats and landform changes using DEMs of difference, with the potential to also map SAV and bathymetry directly (spectral reflectance versus depth predictive models), providing adequate water clarity. This example again highlights the excellent and cost-effective capability of sUAS for coastal ecological monitoring for areas threatened by morphodynamic change and sea-level rise.

### 5.5 Mapping king tide flooding

This final case study presents ongoing efforts to analyze tidal flooding in the urban coastal context, again using Norfolk, Virginia, as a testbed and parallels other examples of integrating UAV imagery into estuarine applications [49]. Norfolk's low-lying and highly complex estuary is dissected by several tributary coastal plain rivers such as the Elizabeth River and the adjoining Lafayette River. With mean mixed semi-diurnal tide range of approximately 1 m, the combined relative sea-level change in the area (combining steric SLR and subsidence) is rapid, and a source of severe concern for future planning as tidal flooding increases in extent and frequency. A number of operational hydrodynamic models are used to forecast flooding in the region and citizen science programs have been used to engage the public in mapping flood extents and calibrating or validating these models. Beyond the use of a GPS and smartphone application to walk the line of a high tide or King Tide flood event, sUAS were seen as an additional resource to validate and refine modeling. In addition, UAS imagery has the potential to monitor impacts such as flooded streets and pavement damage, map debris, and assess vegetation and residential responses.

This case study has undertaken a series of sUAS mapping missions for orthoimagery mosaics across Norfolk, Portsmouth, and Virginia Beach during solunar King Tide events. King tides are routine three to four times per year owing to solunar tidal peaks in the spring and autumn, providing multiple opportunities for integrated sUAS mapping, flood modeling, and in situ water level monitoring. King tides are also a precursor of the future flood hazards facing urban estuaries. **Figure 8** shows one such result for the Larchmont neighborhood along Cambridge Crescent street and triangle park, an open space that likely includes dredged fill adjoining a small breakwater. The image shows the clear contrast of the King Tide flood extent shortly after high tide along the streets. Some areas of vegetation dieback are also evident, and areas that are flooded but surficially disjunct from the creek are indicative of backflow into stormwater pipes. Thus, these images validate geospatial analyses and map flooding that may be underrepresented by hydrodynamic model grids (an error of omission). In addition, sUAS imagery and derived flood footprints are being cataloged and provide a baseline for future change analysis such as shoreline change, marsh migration, and other consequential estuarine changes.

## 6. Autonomous opportunities for estuarine science and management

This chapter's background and case studies suggest that substantial scientific and practical benefits can accrue with the advances of sUAS in estuaries. First, a variety of opportunities and ongoing trends are evident that foreshadow wider use and investigation. Technological advances in UAS generally are seeing application

**Figure 8.**
*King tide flooding in the Larchmont neighborhood of Norfolk, Virginia, is captured by wetted surfaces just after high tide in this UAV orthoimage mosaic (October 29, 2019). Such flood footprint mapping provides for the validation of numerical hydrodynamic models and operational flood forecasts.*

of so-called "Swarm" technology with low-cost UAS. "Flocks" of UAS could be deployed at a more widely scalable level to map ever greater areal extents simultaneously. Miniaturization of platforms, sensors, and improved battery longevity and power are overcoming mission constraints. Fixed-wing UAVs are able to map larger areas, and VTOL and hybrid platforms can fly longer and further distances. Lighter composite materials, stronger power supply, and lighter sensors foretell wider use of LiDAR and hyperspectral imaging. Hyperspectral sensors may open opportunities for early detection of vegetation stress, quantifying carbon stocks, and detection and classification of toxic algal species that are currently not possible or impractical from airborne and space-borne platforms and sensors. sUAS can also enable advances in smallsat platforms and constellations, providing for validation and test-bed experiments in conjunction with optical sensors (Planet, Maxar) and Synthetic Aperture Radar (e.g., Capella Space). Increased availability of satellite Internet and 5G networks will improve the communications and control of UAS-connected systems and their remote or autonomous operation. This, in turn, complements growing cloud-based data information systems, such as Digital Twins (DTs) and datacubes. Soon, the large volume of source UAS data and products can be centrally stored and processed in the cloud, and Machine Learning and AI algorithms are further developed to predict coastal problems and manage responses and solutions. For instance, UAS could be deployed for confirmatory analysis of satellite-detected Harmful Algal Blooms or used for real-time monitoring of technological disasters such as oil spills.

UAS, as we have seen, is opening the door to a more connected, faster-moving, data science approach to coastal estuarine environments, adding to an ecosystem of real-time information collected from satellites, distributed connected IoT sensors, and numerical models. One can envision the next developments using some examples already, such as deployable UAS marine debris and pollution removal (e.g., the *WasteShark* ASV [50]), identifying toxic HABs directly via onboard devices such as the *Planktoscope* sensor [51] and a digital taxonomic library of HAB species, to deliver emergency floatation devices to swimmers or boaters in distress, to track spills and deploy mitigation devices such as (a) booms where human first-responders cannot safety reach or as quickly respond and (b) enabling future science, monitoring, and sustainable resource management. While low-cost, ubiquitous systems may emerge, deployed systems may also emerge as on-demand networks, data-as-a-service, or Drone-as-a-Service (DaaS) commercial operations. For instance, DroneUp LLC is a company moving rapidly into low-cost, rapid package delivery systems using a network of FAA-approved drone pilots in the United States. Certainly, these are but a preliminary and limited view of the potential of UAS science and management applications. Commercial, governmental, and academic institutions are increasingly mainstreaming all such platforms and sensors, with the coming decades apt to continue to see wider adoption and innovation.

### 6.1 System uncertainties to improve

UAS and ASV incorporate and integrate a variety of technologies that, while opening the aforementioned opportunities, also expose potential uncertainties and technological considerations. With the variety of sensors used for bathymetric surveying (single, multibeam, and sidescan sonars), there are also difficulties with communications systems, bandwidth and volume of data transmission (or onboard storage), and complex workflows and costs postprocessing these data. Both UAS and ASVs also rely upon GNSS satellite navigation, which includes the Global Positioning System (GPS) and other constellations, to navigate along predefined routes. However, the accuracy of GNSS positions is variable over time and space and is also prone to occlusion from structures, tree canopies, and Radio Frequency Interference (RFI) [52]. Hence, the prudence of site and situation and the GNSS receiver and space weather may also need to be taken into account. Communications systems with UAS and ASV are usually line-of-sight (LOS), particularly for regulated UAS. However, ASVs may operate beyond visual LOS in an autonomous mode, which raises some concerns about outrunning the coverage of a pilot's communication system. In addition, communications systems are also prone to RFI and may require the use of directional antennas for maximum range. Overcoming some of the limitations of positioning, Inertial Navigation Systems (INS) use accelerometers, gyroscopes, and magnetometer devices to determine craft motion, orientation, and position. These can allow for navigation in GPS-denied environments yet also require calibration and add substantial costs and complexity. Working in estuaries also presents environmental considerations to UxS operations and maintenance. Operators should be well trained in the estuarine and physical coastal environments, including tide ranges and current velocities, meteorology (especially coastal sea breezes and severe weather), and knowledgeable of hardware technological performance under severe conditions such as extreme heat and repeated salinity. Experiences from the case studies presented in this chapter include several examples of lessons learned such as (1) satellite and aerial imagery in mission planning software may not match reality or be out of date; (2) bathymetric and sediment changes in coarse nautical charts may not be reliable for mission planning in small, nonnavigable channels in estuaries; (3) salt is a serious challenge to electric components, including weathering and corrosion from repeated salt spray and salt mineral deposits in moving parts such as thrusters; and (4) extreme heat and humidity can combine to degrade or disrupt systems (such as humidity causing short circuits in navigation or power system wiring, salt encrusting and seizing propellers, or high relative heat indices "frying" echosounders left on between missions in the water).

### 6.2 Safety of operation and regulation

In addition to performance, technological factors affect the safety of operating UAS and ASVs. Operations on busy estuarine or port locations bear special consideration for safety and potentially including onboard collision avoidance systems. These may also require accommodating the limited onboard power/energy system of the ASV or UAS and mission planning (e.g., duration and area extent, the necessity of batter swapping, or potential onboard propulsion and external fuel). Just as ports are busy maritime activity spaces, the same locations often have as busy (or even busier) airspace traffic, often with a greater degree of regulation of UAS. Small ASVs remain the less regulated platform, yet as with any vessel, they must comply with accepted "Rules of the Road" (such as the US Coast Guard in the United States or the International Regulations for Preventing Collisions at Sea 1972 [COLREGs]). Challenging conditions such as busy ports and estuaries with strong tidal currents prompt the use of sea trials to assess risk and compliance with COLREGs [53].

In evaluating the UAS and ASV technologies in general, these considerations for technological, performance, and safety are to be expected of new, emerging technology. With more widespread adoption, the industry, academia, practitioner, and governmental regulatory agencies are likely to develop standards and routine operating procedures. UAS has already seen rapid growth in regulation and the adoption of standards and testing for remote pilots (e.g., Federal Aviation Administration Part 107 testing requirements, airspace regulation, airframe registration, and future remote identification, aka "remote ID"). ASV, in contrast, has not seen as rapid development of technological or regulatory standards, and low-cost, small ASVs are still emerging in the marketplace (e.g., Blue Robotics "BlueBoat' modular, affordably priced ASV [54]). The authors anticipate that the growth of both UAS and ASV platforms and sensors will soon see the acceleration of their regulation that catches up to the early adopters.

## 7. Conclusions

This chapter introduced a sample of the broad technologies and applications of small UAS emerging and rapidly evolving in the field of estuarine science and management. Drawing upon a focus on estuarine shorelines, it is evident that traditional techniques for mapping and monitoring have been far advanced beyond digitizing, transect profiles, and field surveying to include multisensor and multiplatform data acquisition, at speeds, volumes, and levels of convenience never before available. Scientists and coastal management practitioners must consider the various platforms and sensors available and make choices as to their potential limitations as well as advantages. Small aerial vehicles are growing in capabilities to include longer duration flights, greater areal mapping extent, and carry more robust payloads. Small uncrewed surface vessels are also catching up to the aerial sector and remain essential to in situ sampling as well as bathymetric surveys, particularly in turbid waters. New platforms such as the BlueBoat and associated PING echosounder, coupled with GNSS and open-source navigation systems, will allow much wider adoption of these modular platforms for estuary water quality and bathymetric surveys. In small, non-navigable tidal creeks, coarse hydrographic charts may see improved measurements from accuracy between 0.1 and 1.0 m improving to 0.01 to 0.05 m with single-beam eachosounding. Such data will provide for better monitoring, performance, and prescription of adaptions such as living shorelines. Indeed, both UAS and ASV platforms provide the unprecedented potential to collect data as well as to respond to hazards or mitigate environmental problems, pollution, or disasters. As these technologies further advance, we may anticipate more integration and complementarity of data collection, yet also the spatial and computation data infrastructure must also anticipate the growing data volume, rate of creation, and complexity. Academia and other sectors must also develop inter- and transdisciplinary approaches to education and training to maximize the benefits of UAS. One distinct finding of this research was the variability of uncertainty and reliability of shoreline data across sources over time. As shoreline data become more accurate and precise from UAV acquisition (a few mm to a few cm as compared to 10's of cm to m in traditional aerial photography or chart data), this may improve the robustness and reliability of shoreline change statistics. Techniques such as the USGS DSAS WLR method would naturally weight the more recent, accurate shoreline data, which could reduce near-term prediction or extrapolation of uncertainty. In turn, more accurate and precise shoreline measurements of alternative living shoreline designs measured by ASV and/or UAV LiDAR could allow more useful prescription and guidance as to living shoreline designs given background erosion rates and future wave action under sea-level changes. As climate change, sea-level rise, and coastal development continue to pose immense challenges for coasts, UAS technologies can at least assist adaptation and sustainability of social-environmental systems in estuaries.

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