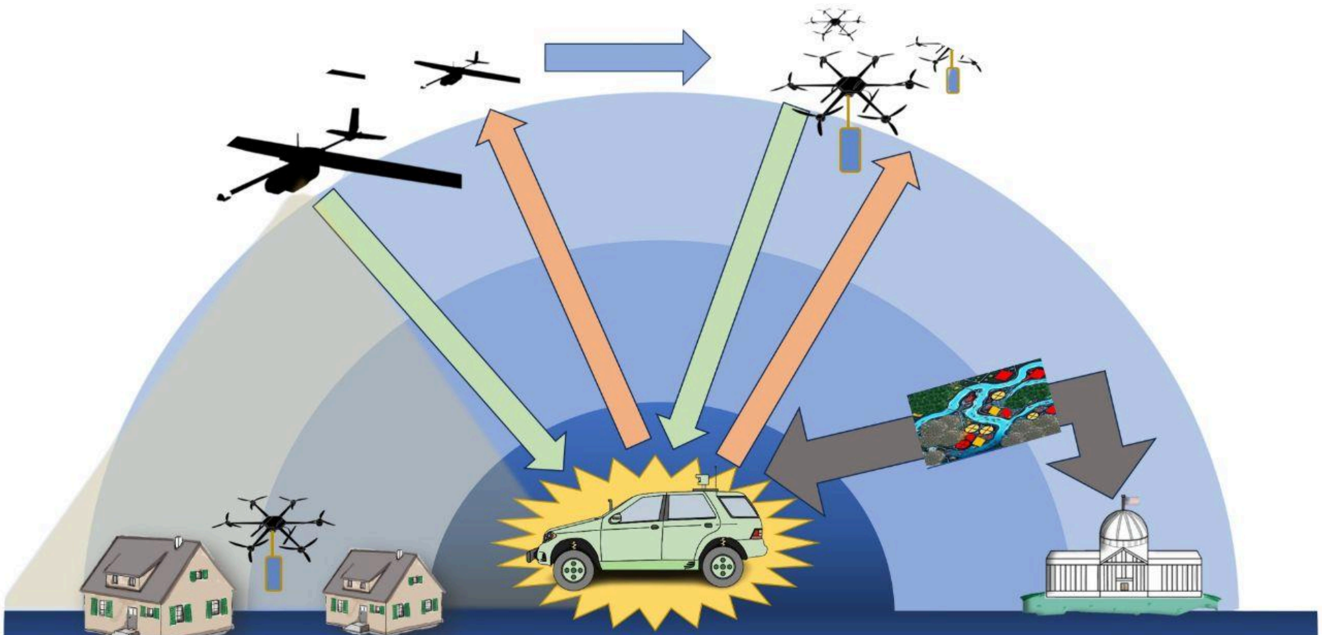
NASA Gateways to Blue Skies Competition: Advancing Aviation for Natural Disasters

R.E.C.O.V.E.R.

RAPID EVALUATION, COORDINATION, OBSERVATION, VERIFICATION & ENVIRONMENTAL REPORTING

BOSTON UNIVERSITY



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ABSTRACT

In response to the increase in natural disasters worldwide, our team proposes an aviation-centric system to aid in one phase of natural disaster management, addressing the objectives set forth by the 2024 NASA's Gateways to Blue Skies Competition. Since floods constitute approximately 90% of natural disasters in the United States, they represent a substantial threat to public health, inflict considerable damage to property, and incur significant financial costs [1]. The Department of Health and Human Services stated that 133 million Americans were at risk of experiencing flooding just in Spring 2024 [2]. One of the challenges encountered after a flood is comprehending the full scope of the flood's contamination and damage. When assessing areas during flood recovery, considerable resources and safety risks are associated with navigating contaminated waters after a flooding event. Conducting damage assessments and managing debris can be an extremely labor and time-intensive process, often taking months in large-scale floods (such as the flooding seen in VT), putting strain on limited personnel resources [54]. To mitigate this issue, our team evaluated the capabilities of a drone swarm to expedite flood recovery and inform on the allocation of funds post-disaster. Our team gathered feedback from representatives at the Federal Emergency Management Agency (FEMA), United States Coast Guard (USCG), City of Providence Emergency Management Agency, the Federal Aviation Administration (FAA), and various water quality analysts, ensuring our system meshes with and complements existing practices. We demonstrate how our system aligns with these practices throughout the paper. In addition, the resulting system's deployment strategy and the team's proposed path toward implementation by 2035 are described.

Our proposed system, RECOVER (Rapid Evaluation, Coordination, Observation, Verification, & Environmental Reporting), can rapidly survey an area of approximately 80 mi^2 in approximately 4 hours, enabling swift identification of floodwater hazards and early mitigation of health risks in the flood recovery phase. Since the original proposal, our team gathered additional feedback from potential stakeholders and expanded on the risk mitigations and implementation barriers of our system. Furthermore, the integration of RECOVER's components and FAA framework in which the system will operate were defined. The quick collection of damage assessment data can significantly aid in the economic recovery of the affected area. Finally, our system substantially benefits local governments by relieving pressure on scarce personnel resources and shifting their focus from damage assessments to more impactful community assistance. This capability lowers government costs and minimizes residents' health risks [3, 4].

TABLE OF CONTENTS

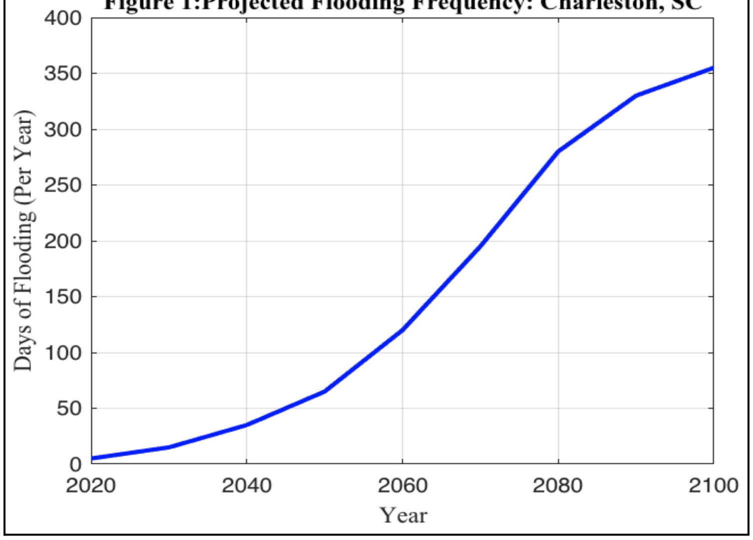
FIGURES

APPENDIX

INTRODUCTION

Due to the effects of global warming, an increase of at least 500% in precipitation and river flow is expected over the next 30 years [5][55]. The frequency of flooding events is predicted to increase more than any other natural disaster, suggesting that floods must be a significant target in climate change preparation [6][7]. These incoming crises indicate a great need for advanced flood management planning so governments will be equipped with modern and timely technological solutions. Such changes to the world's climate can already be seen, as the turn of the year has witnessed significant flooding events in California, Texas, South Carolina (Figure 1 [8]), and Mississippi [9]. Floodwaters pose a severe health risk, even days after the flood. Although much emphasis is placed on rescue efforts during a flood, the recovery stage also greatly strains federal agencies and local governments. The allocation of funds and aid often requires deploying specialists for flood damage assessments, costing significant time and money [10]. In addition, rigorous water sampling is often conducted to ensure public safety and the return to regular life, typically elapsing over several weeks to months. It can be challenging to sample floodwater as it is often done manually in hard-to-access locations [11]. Furthermore, sampling floodwater can expose personnel to chemicals, bacteria, and other harmful pathogens [53].

Figure 1:Projected Flooding Frequency: Charleston, SC



State governments and FEMA require extensive documentation of flood damage, which can be extremely difficult for local officials trying to navigate the disaster recovery process. A traditional Preliminary Damage Assessment (PDA) can take 7-10 days to complete before any collected data can be sent to local government agencies. It can take months until a formal damage assessment is completed and residents are reimbursed for any damages to personal property [12]. Some of the challenges associated with flood recovery practices are shown below in Figure 2. Drones and satellite imaging are currently utilized for flood surveillance and provide valuable information about a disaster site. Satellite images sourced in real-time may be obscured by atmospheric conditions in inclement weather. Conversely, UAVs can sense features in terrains that are too small for satellites to detect. However, managing collected data requires at least one operator per drone and significant integration efforts, which is neither time nor cost-efficient. This financial and physical burden can be alleviated by introducing autonomous unmanned aerial vehicles (UAVs), accelerating the PDA process, and minimizing the risks associated with working in the field.

Brief Overview

RECOVER (Rapid Evaluation, Coordination, Observation, Verification & Environmental Reporting) is a drone swarm-focused program that fixates uniquely on tracking the spread of debris and water contamination. Its purpose is specifically for flood recovery management when survivors have been evacuated and floodwaters are beginning to subside. The system only requires 1-2 operators to survey an 80 mi^2 flooded region within 4.5 hours. In addition, the system is stored in a modified SUV, allowing for mobility and more extensive coverage within a single paid workday. An

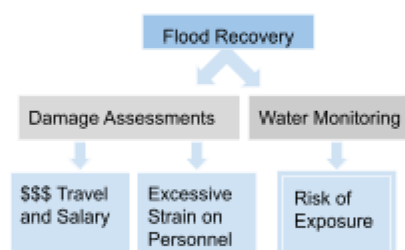


Figure 2: Existing Flood Recovery Practices

operator first begins by identifying the flight area for the fixed-wing UAVs; these will start by autonomously surveying the area, capable of covering a distance of about 40 miles before needing to turn around. These drones are fitted with high-resolution cameras, capable of capturing fine details from their cruising altitude of about 300 feet. While the fixed-wing UAVs complete their initial surveillance round, the operator prepares hexacopter drones. The hexacopters are fitted with a water-sampling system (WSS). Operators can mark "hotspots," i.e., places of interest (water reservoir, sewage systems, etc.), which will guarantee coverage by multiple hexacopter devices. The SUV has additional batteries, allowing operators to redeploy drones effectively. While both UAV types complete their tasks, the collected information is relayed to the SUV's onboard computer, displaying a live map of water quality, debris location, and velocity. Once the map is finalized, all UAVs are called back to their home positions via the ground control station (GCS) contained in the SUV. In addition, while a 6:8 ratio (Fixed-Wing: Hexacopter) has been calculated to cover areas of 80 mi^2, the modular nature of RECOVER allows the system to be adapted based on the priorities of the responding agency. Teams deploying RECOVER can modify the system to have a surveillance-based bias over water sampling (or vice versa), making it suitable for most missions.

Technical Description & Operation Timeline:

Before the system can be deployed, it is verified that first responders have left the disaster site and that the local airspaces are mainly empty. Additionally, RECOVER will input flood data from preexisting geospatial databases such as the National Flood Hazard Layer (NFHL) [50]. Reserving the airspace for RECOVER via a NOTAM (Notice to Air Missions) will likely not pose any issues, as close communications with the FAA are expected throughout the system's life cycle. This restriction will be marked as temporary, rendering it forbidden for other aircraft to navigate within a prescribed square mileage and altitude (see page 12). In addition to setting a NOTAM in effect, additional waivers would be needed from the FAA, primarily covering section 107, which would lift many typical airspace restrictions found with UAVs today. For example, a waiver for section 107.35 would allow a single RECOVER operator to simultaneously pilot multiple drones. Once it has been validated that it is safe for RECOVER to be deployed, operators navigate to predefined locations in a series of modified SUVs, which serve as the Ground Control Station (GCS). These vehicles are altered to withstand low to moderate flood water depths, featuring armoring such as skid plates to protect the undercarriage from any sharp debris. Then, the operator begins preparing the communications network, which will interact with RECOVER and the agencies involved. The fixed-wing UAVs (which come with wings removed for transportation purposes) are assembled and deployed. The fixed-wing UAVs' first pass occurs at 300 feet from the ground. This low-altitude cruising, paired with a high-resolution and high field of view (FOV) camera, allows for a high-definition mapping of the disaster site. This initial swarm is also programmed to overlap its passes from different angles, allowing for the 3D generation of large debris while also being able to distinguish between artificial or vegetative material. RECOVER is fitted with a convolutional neural network (CNN), which will pinpoint any areas of interest for the hexacopter drones. Once the initial surveillance round is complete, the fixed-wing UAVs return to the GCS, where some will be redeployed (with new batteries) for additional monitoring. For the remainder of RECOVER's mission, the fixed-wing drones operate at higher altitudes, 1000-2000 feet, depending on wind and climate conditions. At this stage, the hexacopter drones take over the mission, navigating to any hotspots marked by the system and operators. When a hexacopter arrives at one of the sites, it lowers itself to the water surface and collects samples via the water sampling system (WSS). Here, it can acquire basic information about the water quality, though it will need to bring it to the GCS for in-depth bacterial and chemical analysis. The hexacopters are additionally retrofitted with a digital camera to capture any up-close images of damage. The hexacopters will continue to execute these tasks until all marked points have been visited. The collected information will then be uploaded to an onboard computer in the GCS, which will be sent to county and federal officials for further processing. The deployment of RECOVER is illustrated below in Figure 3.

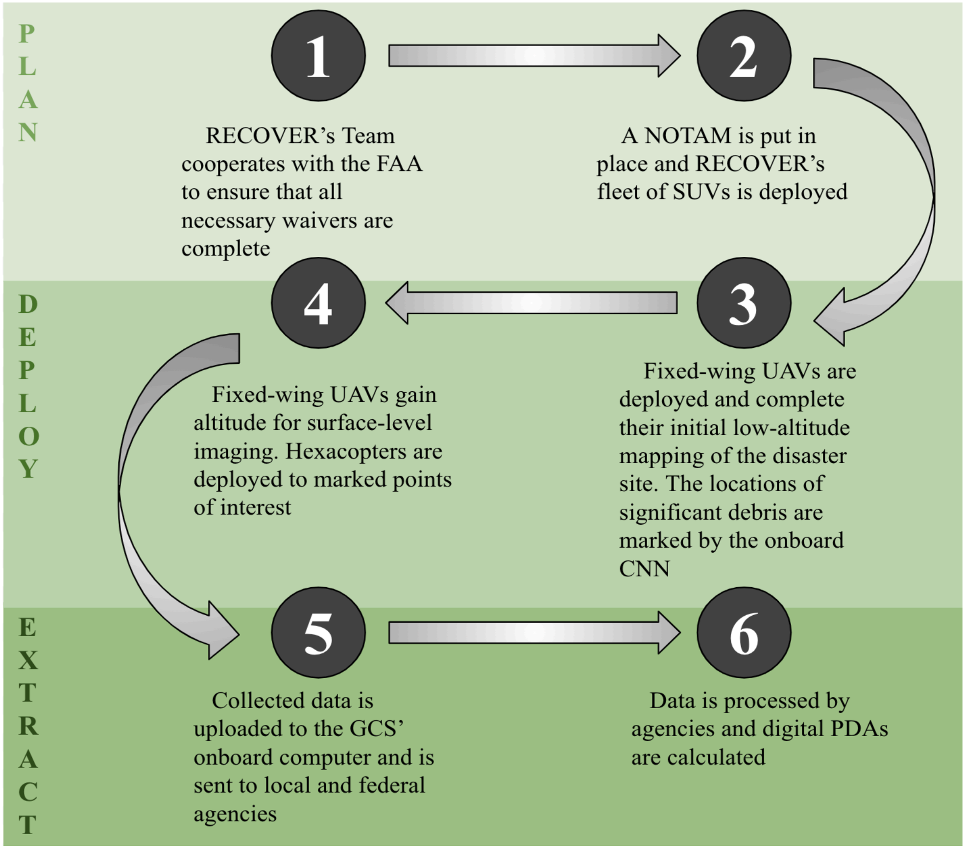


Figure 3: RECOVER Deployment Timeline

PROPOSED SOLUTION

Figure 4 below illustrates the RECOVER system. On the left, the diagram highlights the current challenges in the flood recovery process, while on the right, it displays outputs from our system. Various aspects of RECOVER, including communication, hardware architecture, water quality monitoring, and mapping, have been considered to ensure the proposed UAV swarm system operates efficiently.

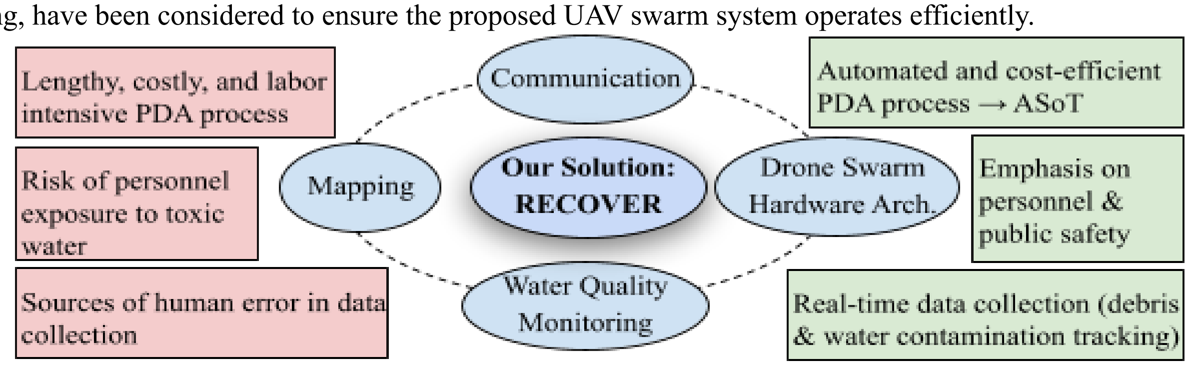


Figure 4: Sub-system Overview

Communications

A hybrid free space optics (FSO) and radio frequency (RF) communication system [13] will be implemented to maximize bandwidth, range, and reliability in post-flood conditions [14]. For a heterogeneous drone swarm [15] consisting of different types of UAVs, key considerations will include range beyond visual line of sight (BVLOS), low latency data transfer for machine-to-machine (M2M), and machine-to-GCS communication. Drone swarm communications involve the creation of mobile/flying ad hoc networks (MANETs/FANETs) and wireless mesh networks (WMN), with each UAV acting as a network node [16]. FANETs can be established via satellite communication, radio frequency, cellular networks, and, prospectively, free space optics [17].

The proposed communication system will combine FSO and RF. FSO allows for high-capacity data transfer with low latency and ease of deployment, both necessary for RECOVER. It is limited by alignment issues and sensitivity to atmospheric disturbance, but the technology is expected to mature by 2035, with ongoing research integrating machine learning, spatial diversity, and adaptive optics techniques [18]. RF is an operationally proven [19] platform for long ranges used in tactical settings via wireless software-defined radio and IP mesh, enabling secure BVLOS communications [20]. This hybrid approach will incorporate the benefits of both systems while ensuring reliability.

Fixed-wing drones will have RF transceiver nodes and FSO transceivers, and hexacopters will be equipped with just RF nodes. Communication via license-free RF (1.20-5.00 GHz) will occur for most M2M communications, up to 18.5 miles per link, enabling real-time data transfer for swarm positioning, localization, and sensing at rates up to 87 Mbps [20]. For large data transfers across longer distances, routing algorithms, such as Dijkstra's, will relay data through the shortest path of RF nodes to a fixed-wing drone. The fixed-wing drone will receive the data and move into the visible line of sight (VLOS) of the GCS FSO Link. While the range is limited to about 3 miles, the FSO will allow extremely high bandwidth data transfer rates of 1.25Gbps [21] back to the GCS, which will perform the necessary computation for mapping (Appendix B2). Figure 5 shows the paths of data transfer. In the event of loss of communication, the drone(s) will autonomously attempt to reestablish an RF connection. If unsuccessful, the drone(s) will evaluate its remaining power and range capabilities and return to the deployment site.

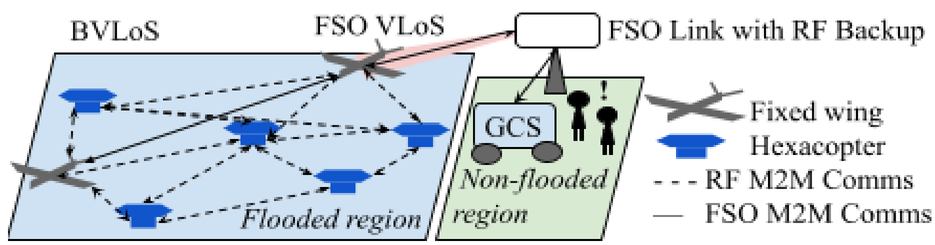


Figure 5: Communications Diagram

Mapping

Property damage is determined using floodwater depth, velocity, and water contamination level. However, many flood models focus on “slow-rise” water depths, impacting damage estimates [22]. RECOVER will use preexisting geospatial image data and communicate with federal, state, and local government employees to determine the system’s target areas. The NFHL contains valuable information regarding flood hazards, particularly the base flood elevations, flood hazards, and levees. After receiving the preliminary information, the fixed-wing drones will take site images on their first pass and send them to the GCS. Then, the GCS will use a structure-from-motion (SfM) photogrammetric measurement system to create a 3D map of the flooded area to provide information on the flood’s span and depth. The GCS will utilize a high-performance computing (HPC) center to reduce computational time. Anticipated future advancements in computing efficiency and data management will also increase the system's viability. SfM is implemented by triangulating many images of one area, which may take up to 2 hours [23]. Fonstad et al. successfully employed SfM using images from a 10.0-megapixel resolution camera from 130 ft in the air [23]. If RECOVER employs cameras with a similar resolution, each image will encompass a 0.06 mi^2 area. However, the cameras must have a frame rate that is high enough to compensate for the fixed-wing UAV’s flight speed [40]. Given a floodplain with an area of ~80 mi^2 (i.e., the city of Baton Rouge, LA [42]), 6 drones flying at 22 mph can survey the area in around 150 minutes (Appendix B1). Advantages of SfM include a relatively high ease of use and a low computational cost, as well as flexibility in changing image resolution and viewpoint [23][40]. In addition, moderate turbulence surprisingly aids in the image process because the conditions induce slightly varied fields of view, providing the SfM system with a larger range of data points. As the map is generated, the fixed-wing drones will return to the area to assess the water level and debris.

The fixed-wing and hexacopter drones will be programmed with a CNN to identify points of interest and avoid collisions. The CNN will be trained pre-deployment on images of objects of interest, such as vegetative and non-vegetative debris, indicators of structural damage in buildings and bridges, downed power lines, and obstructions in the drone's flight path. The images for training will be obtained from open-source data. Processing the image data locally allows for reduced latency in communication [23], allowing the drones to maneuver around obstacles in their flight path. The current (as of 2024) state-of-the-art CNNs, such as YOLO or EfficientDet, are designed for real-time execution [24]. In addition, algorithms like Dronet can reach 5-18 frames per second (fps) with 95% accuracy [25].

The drones will track the path of debris in flooded areas to identify major road obstructions, drain blockages, and still-water regions to ensure ideal water sampling conditions. Large-scale particle image velocimetry (LS-PIV) will be used to calculate the floodwater velocity at hotspots. LS-PIV is a popular, fast, and cost-effective algorithm that can run on the drone's flight computer, requiring only a small amount of processing power and providing real-time velocity data [26, 41]. Lewis et al. implemented LS-PIV using drones with similar results to fixed cameras; the tracking error was less than 10% [39]. The drone's flight computer will have low-power electronics with 8 GB of RAM (Appendix A7).

Water Quality Monitoring

In alignment with the water quality standards set by the Environmental Protection Agency (EPA), the US Geological Survey (USGS), and recommendations from interviewed municipal water quality specialists, our UAV swarm will assess turbidity, temperature, dissolved oxygen (DO), pH, nitrate levels and test for harmful bacteria, such as E. coli, in floodwater [27, 28, 29]. In addition, depending on a specific area's needs, sensing capabilities can be added in the future. Turbidity, DO, and pH are indicators of harmful chemical presence in water while nitrate levels indicate the amount of sewage/fertilizer. Small, reliable probes for these measurements are already being tested on drones [30]. However, traditional methods for monitoring bacteria levels require collecting a large volume of water (~1 liter) and testing in a lab, taking 1-2 days [31]. Our team proposes portable Loop-Mediated Isothermal Amplification (LAMP) tests to streamline this process. While these tests for in-field use are in development, portable LAMP tests for various pathogens (albeit not E.Coli) are already available commercially. Research by Seunguk Lee et al. from the University of Singapore has demonstrated that LAMP tests can accurately detect E. coli in water samples as small as 5 mL within 30 minutes [32]. Leveraging this research, a robust, rapid, portable bacteria testing system will be implementable by 2035 capable of analyzing 5mL samples collected by rotorcraft drones from various remote sampling locations. Additionally, the collected water samples can be sent to a laboratory for analysis to detect harmful chemicals such as lead, mercury, and arsenic. While more costly, emerging portable metal detection sensors are also available and can be integrated into the RECOVER system for immediate field analysis [52].

Hardware Architecture

The first device to be deployed is the fixed-wing UAV, designed to survey the disaster site from a distance. Estimated to reach distances of about 30 miles (Appendix B3), these UAVs will feature VTOL (Vertical Takeoff and Landing) and a high-resolution camera with optical zoom. Built-in camera features, such as optical stabilization, ensure the capture of detailed images in turbulent air conditions. Once the first surveillance round is complete, hexacopters will be deployed for more thorough imaging and local water sampling, and the fixed-wing UAVs will begin their additional rounds.

The hexacopter drones, equipped with a Water Sampling System (WSS), are heavier and have a shorter range than fixed-wing drones. Their six-propeller design and 6-axis accelerometer provide stability in breezy conditions. These drones feature a digital and an event-based camera for capturing close-up images of key areas while quickly avoiding hazards. Although event-based cameras continue to be expensive, many of their capabilities can be mimicked using conventional software [33]; event-based cameras are also active points of research in the UAV field and will decrease in price within the next decade. The UAV will have a buoy-like base to ensure efficient water collection, allowing for brief water landings. It will also carry the WSS; featuring a revolver-like base, the WSS will house several 5 mL cuvettes, which will be collected when the drone lands on the water's surface. In addition, the sampling cuvette can be swapped out to store water for tests requiring larger sample volumes (such as for detecting trace amounts of lead and arsenic). After an approximate 1-hour flight time, the device will return to the GCS, where the samples will then be tested for bacteria by the system operators. The hexacopter's shell will be designed for easy battery removal and replacement, facilitating quick redeployment.

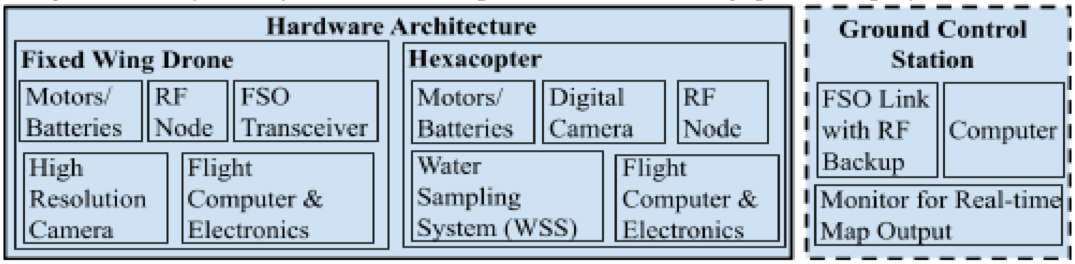


Figure 6: System Architecture

Operational Scenario

With both drone types in tandem, disaster recovery teams can gather measurements significantly faster than in conventional practice. A robust, multi-hour mission allows for detailed imaging, debris tracking, and cumulative water quality mapping, enabling informed decision-making. Post-operation, the collected data will be used for a streamlined reporting process to create preliminary damage assessments for local governments within a few hours. According to Dr. Clara Decerbo, the Director of the Providence Emergency Management Agency (PEMA), PDA construction is often time-consuming, especially if the agency is understaffed. RECOVER's operational tasks are described below in Figure 7.

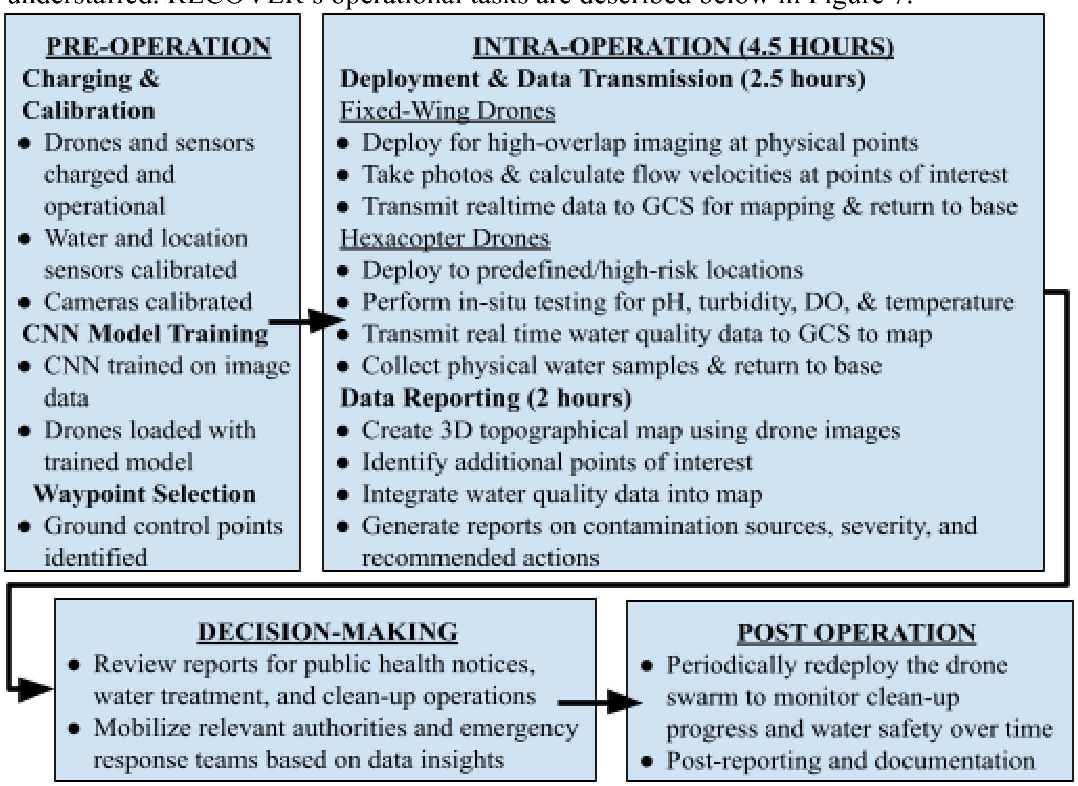


Figure 7: Operational Scenario

FEASIBILITY

Presently, there are technological limitations that inhibit RECOVER's feasibility. However, many of the proposed technologies have a relatively high TRL, validating a high confidence in achieving system readiness by 2035. The TRLs are summarized in Figure 8. Lower TRL technologies are in active research and are expected to mature by the proposed timeline in Figure 9.

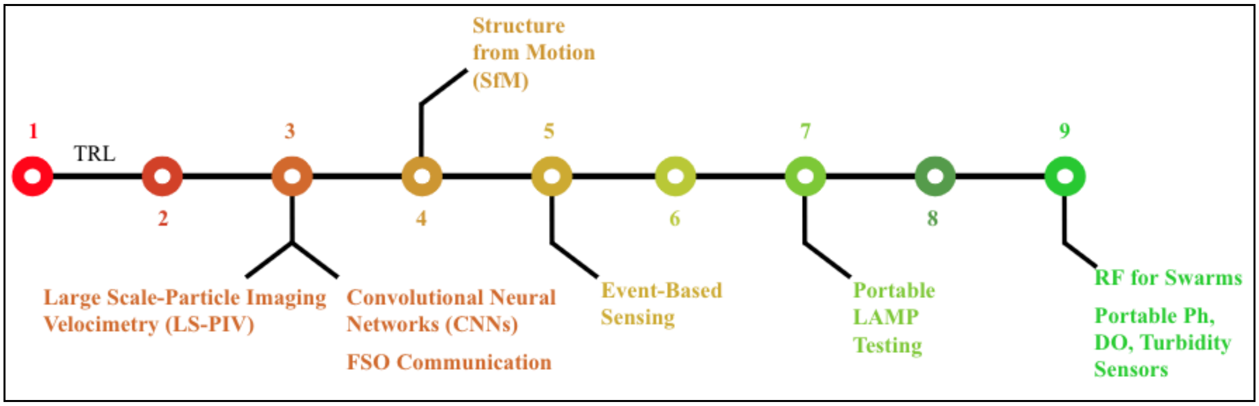


Figure 8: Technological Readiness Level (TRL) of System

The implementation of RECOVER will include the extensive development of subsystems, infrastructure, and operator training. Regulation-compliant development of different subsystems will occur in parallel with careful attention to technologies being published in academia and industry. At the halfway point of the timeline, system integration will evaluate partial and full-scale system functionality before rigorous system qualification in field and test environments.

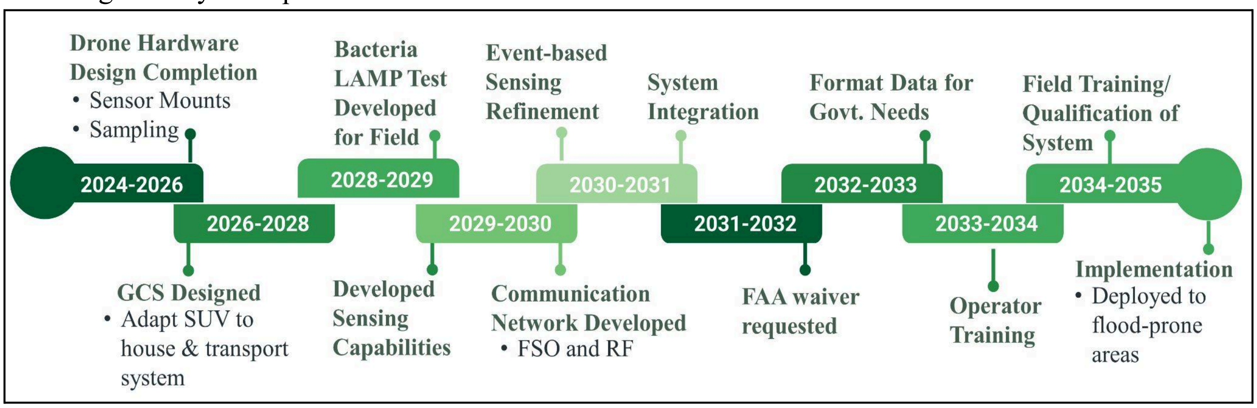


Figure 9: Proposed Implementation Timeline

System Integration

The maturation of subsystem technology begins with research and development in collaboration with partners in industry and academia with NASA insight over key progress. Subsystem preliminary and critical design review assessments need to be achieved on all aspects of the system (i.e. hardware, software, communications, etc.) before integration into RECOVER. Real-world operational scenarios are simulated in a test environment, and subsystems are assessed for correct performance. Critical sub-integrations include the electromechanical integration of hexacopter hardware and water sampling system, data transfer via communications hardware and GCS interface (e.g. streamlining data format), drone and swarm system metrics telemetry to GCS (i.e. dashboard with speed, power, data capacity, etc.), and software and algorithm integration with camera and sensing hardware. The information on flood scope will be uploaded to an onboard computer in the GCS. Integrating both preexisting GIS data and data from RECOVER, a 3D topographical map will be generated with a simple, intuitive UI accessible to recovery personnel during the debris cleanup efforts. Agencies are already shifting towards more automatic assessment processes [51]. After data collection is finished, RECOVER will automatically fill out FEMA's damage assessment form by tagging images with descriptive words using the convolutional neural network. Coordinates of damaged areas and areas in need of debris removal will be tabulated to inform clean-up crew contracts and estimate costs. The collected data on flood water quality will be tabulated and sent to agencies such as FEMA and the Environmental Protection Agency (EPA).

Implementation Barrier Management

Since RECOVER requires operators, one hurdle that must be overcome is personnel training. Operators will need training to process and upload data to RECOVER and correctly operate the bacteria testing device. Given that many areas may lack skilled staff, the RECOVER system is designed to be user-friendly, necessitating no more than an hour of training before deployment. This is to be done via a series of interactive training videos as well as a hands-on demonstration and test. Standardized operating procedures will also be provided for personnel to reference. Additional certification through the Federal Aviation Administration (FAA) will be required. One to two personnel are required to be Certified Remote Pilots (Small UAS Rule Part 107) [45] to oversee the operations of the drone swarm. Additional waivers will be required as RECOVER consists of multiple autonomous drones beyond the visible range of sight (BVLOS) [45]. For most operations, RECOVER will fly within the 400-foot maximum for class G airspaces [34]. However, RECOVER's goals of performing "assessments supporting disaster recovery" align with the FAA's emergency recovery operations and qualify it for expedited authorization waivers to access controlled airspace, if required [46].

FEMA has implemented restrictions on processing and storing personally identifiable information, such as faces and license plates [44]. Although RECOVER will temporarily store many images of a flooded area during the first pass of imaging, only topographical data will be processed. In addition, RECOVER's CNN algorithm will not be trained on sensitive information.

Risk Mitigation and Matrix

RECOVER must be resilient to varying environmental conditions and partial subsystem component failures to minimize risk and maximize utility. Hence, considerations for worst-case scenarios will be taken into account with high factors of reliability. A series of risks and corresponding mitigation strategies are tabulated below in Table 1 to account for potential barriers to implementation and usage. The likelihood and severity of these risks are rated from 1-5 with 5 being the maximum.

Table 1: Risks and Mitigations

Key Risk	Risk Level (Likelihood, Severity)	Mitigation
Conditions make system unable to deploy	(2, 2)	- Monitoring of weather conditions (fog, wind, etc.) prior to mission - Pre-planning of routes
Hardware component or system failure	(3, 5)	- Rigorous testing & qualification prior to field use - Interval maintenance & calibration - Redundant components / modular design for replacement
Contact with Contaminated Water Samples	(5, 2)	- PPE, sealed containers, and hazard stickers provided in GCS - Operators trained for sample handling per EHS guidelines
Drone collision	(5, 5)	- Rigorous testing & qualification of algorithms prior to field use (with factors of safety) - Integration of event-based sensing cameras
Software failure	(3, 5)	- Option for teleoperation with human-in-the-loop control with software-defined pre-set functions
Personnel error	(2, 3)	- Comprehensive operator training with feedback - Operators dispatched in pairs - Software-integrated fail safes and thresholds - Standardized documentation for reference (SOPs)
Loss of communication	(5, 5)	- Redundant and resilient testing of comms system - Pre-set rehoming points for reconnection attempts - Backup routes for individual drones auto-generated

		- Pre-Deployment Check
Incident Aviation Aircraft Interference	(3, 5)	- Visual observer patrolling for other present aircraft - Monitoring of air traffic through flight radars - Communication with ATC for appropriate clearances - Use of UTM to detect other aircraft - Stop-all protocol: Drones ordered to land if other aircraft are detected
Power considerations	(2, 4)	- "Safe" power thresholds are designated - Redundant power sources & additional batteries on site - Monitoring of system health metrics during deployment - Power allocation and prioritization - Redundant power sources
Data transfer	(1, 3)	- Physical hardware backup on drones for data storage

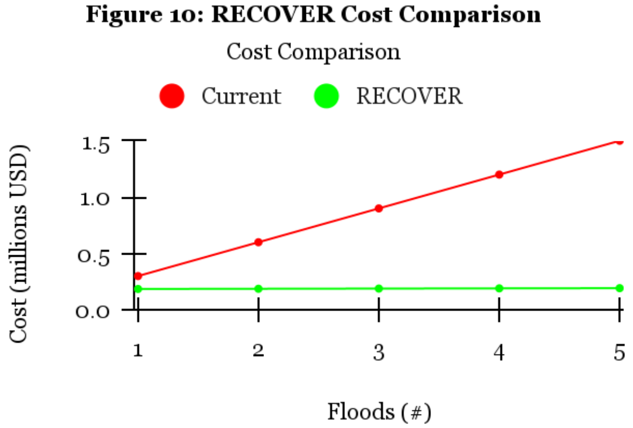
SOLUTION IMPACT

Major flooding events cost approximately $300,000 in personnel travel and water sampling expenses [12, 29]. Our system has a one-time cost of about $185,000 ensuring consistent savings with each event (Appendix A8). Additionally, once purchased, the system can monitor minor floods as well, further reducing costs. The cost of reusing the system is only ~$2,000/instance (Appendix A9).

Case Study: Hurricane Harvey

In 2017, Hurricane Harvey resulted in catastrophic flooding and serves as a case study for demonstrating the application of our system. The state of Texas was devastated, with residents displaced from their homes and streets filled with debris for years after the disaster [48]. The expenditures for Hurricane Harvey for fiscal years 2017 and 2019 were approximately $113 million to the Texas Department of Transportation, which included debris removal, road repair, and bridge inspections. [49]. Debris removal efforts were slow, taking around 3-6 months. Piles of the waste left outside were "magnets for mold, mosquitoes, and diseases," raising health concerns about the pace of the removal efforts [47]. Notably, Houston "decided which neighborhoods to enter first by assessing the level of damage and accessibility" - a process which can take up to a month for an area surveyed, according to Donald Grantham, an Emergency Management Specialist at FEMA.

Figure 10: RECOVER Cost Comparison



RECOVER could have mapped out these hazards an order of magnitude faster, significantly reducing the time taken to survey the area and allowing Texas residents to quickly resume everyday life. In addition, the cleanup efforts put a notable strain on personnel, with debris removal companies noting that they were understaffed during the disaster [47]. RECOVER requires only 2 personnel to survey 80 mi^2 areas in a few hours, reducing the strain on human resources.

Local agencies were tasked with sampling water quality, especially near industrial facilities and hazardous waste sites. The EPA, Texas Commission on Environmental Quality (TCEQ), and other local and state agencies continuously monitored water quality near wastewater facilities [35]. Our system will reduce the personnel needed for water quality monitoring and provide information on chemical and bacteria spills more rapidly than traditional testing procedures. This accelerates the overall recovery effort and enhances workforce safety by minimizing direct exposure to floodwaters, large debris, and downed power lines, which RECOVER could have highlighted and mapped out for easier removal.

Furthermore, since local governments own the UAVs, our drones would already be equipped to relay information to assisting agencies. Insurance companies like Allstate heavily utilized drones and GIS imaging, reporting a threefold increase in daily damage assessments per adjuster with drone use [37]. Companies have also provided GIS and up-close drone imaging, similar to our system's capabilities [38]. However, due to the swarm aspect of our design, imaging data would be generated more rapidly and could provide one ASoT (Authoritative Source of Truth). Our drones, functioning within the FAA's regulatory framework, would have provided local governments with data collection to streamline the submission process to FEMA for aid.

Stakeholders:

Since the initial RECOVER system proposal, feedback was gathered from various stakeholders. Our team identified FEMA, local governments, the U.S. Coast Guard, the U.S. Geological Survey, and the EPA as stakeholders in our system; however, there can be more agencies that will utilize the data collected by RECOVER. Each group requested the following information in addition to our initially proposed functionalities (Figure 11).

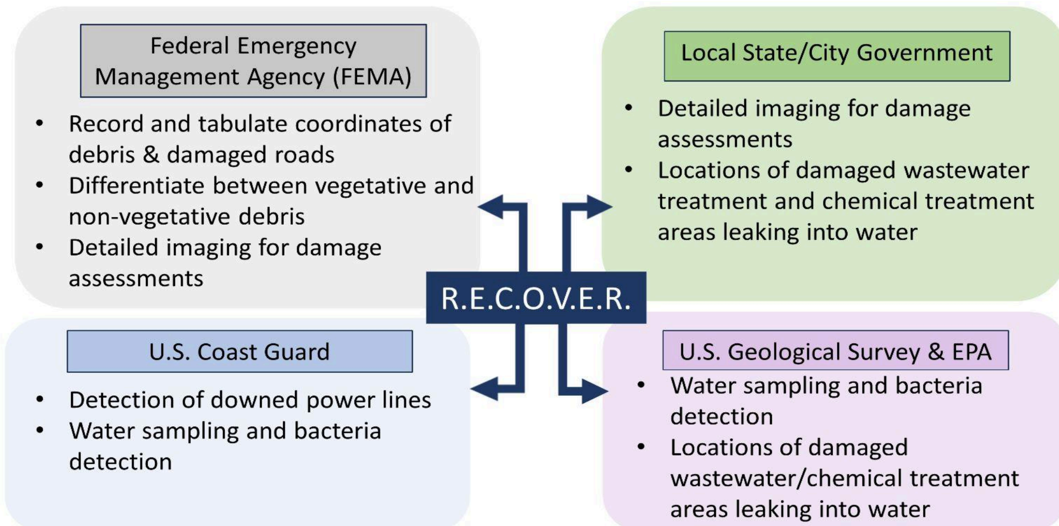


Figure 11: Stakeholder Requested Functionality

CONCLUSION

Flooding events are predicted to increase in frequency due to climate change, necessitating improvements in flood disaster management. The long-term expected increase in the frequency of these events implies potential strains in existing procedures. A practical solution to this problem is a reusable heterogeneous UAV swarm-based system that semi-autonomously maps the disaster site, tracks debris location, and collects water samples. The gathered information would be transmitted to the GCS (Ground Control Station). Once all relevant data has been received by agents on site, the damage map can immediately be sent to government agencies and FEMA headquarters for further analysis. As highlighted in the Hurricane Harvey case study, drones are increasingly utilized in disaster response. Although federal agencies often approach new technologies with caution, our system is engineered for easy integration. RECOVER meets the specific needs of these agencies and is designed to comply with FAA regulations.

RECOVER utilizes existing practices, such as drones for surveying areas, and proposes new and innovative technology, such as hybrid-FSO communications, portable Loop-Mediated Isothermal Amplification devices for rapid bacteria detection, and computer vision algorithms. Combined into one system, the technologies outlined in the proposal allow for expedited implementation, enabling government agencies, impacted businesses, and residents to recover quickly from the flood.

APPENDIX

A1: Drone Weight Estimation, Rotorcraft (Top) and Fixed-Wing (Bottom)

Component	Estimated Weight (g)
Frame	2000
Motors (x6)	1200
5MP Camera	200
Event-Based Camera	100
Battery	1500
Water Sampling System	500
Onboard Electronics	400
Total Weight (Hexacopter)	**5900**

Component	Estimated Weight (g)
Frame	1500
Motors (x2)	300
Camera	700
Battery	1000
Onboard Electronics	400
Total Weight (Fixed-wing)	**3900**

A2: Drone Hardware Cost Estimation, Rotorcraft (Top) and Fixed-Wing (Bottom)

***All total system cost estimates assume a system of 6 fixed-wing and 8 hexacopter drones.**

Component (Quantity)	Price Per Unit (USD Est.)	Adjusted Price (Low/High)	
Frame & Shell (1)	200-400	200/400	
Motors (6)	15-40	90/240	
Digital Camera (1)	30-40	30/40	
Event-Based Camera (1)	100*-3000	100*/3000	
Battery (1)	500-800	500/800	
Onboard Electronics (1)	300-400	300/400	
Water Sampling System (1)	200-400	200/400	
Total Price (Rotorcraft)	———————————	**$1320.00**	**$2280.00**

*Event-based cameras, though expensive, can be emulated by regular cameras with software

Component (Quantity)	Price Per Unit (USD Est.)	Adjusted Price (Low/High)	
Frame & Shell (1)	100-300	100/300	
Motors (2)	15-40	30/80	
Camera (1)	900-2500	900/2500	
Battery (1)	100-400	100/400	
Onboard Electronics (1)	200-300	200/400	
Total Price (Fixed-Wing)	———————————	**$1330.00**	**$3680.00**

A3: Water Quality Testing Cost Estimation*

***Note, due to the adaptability of the WSS, the onboard components/testing equipment can vary, impacting overall cost**

Component (Quantity)	Price Per Unit (USD Est.)	Adjusted Price (Low/High)	
Turbidity Sensor (1)	100-300	100/300	
pH Sensor (1)	200-400	200/400	
Dissolved Oxygen Sensor (1)	80-100	80/100	
Rapid Bacteria Test (1)	300-400	300/400	
Total Price (Water-Testing)	———————————	**$680.00**	**$1200.00**

A4: Hybrid Free Space Optics / Radio Frequency Communication Infrastructure Cost Estimation

Component (Quantity)	Price Per Unit (USD Est.)	Price
RF Node* (14)	5000	70000
RF Base Link (1)	5000	5000
FSO Transceiver (6)	500	3000
FSO Ground Link (1)	20000	20000
Comms Command Center (1)	10000	10000
Total Price (Comms Infrastructure)		**$108000.00**

* Our estimate uses a quote from Domo Tactical Solutions' BLUSDR-30-2x1W-BluSDR-Module

A5: Ground Control Station Cost Estimation

Component (Quantity)	Price Per Unit (USD Est.)	Price
SUV (1)	35000	35000
Computer (2)	1500	3000
Monitors (3)	300	900
Power Generator (2)	1500	3000
HPC - System (1)	566	566
Total Price (Ground Control Station)		**$42466.00**

A6: High-performance Computing Center Cost Estimation

Compute Time (Hours)	5
Cores (Quantity)	896
Computing cost (USD per core-hour)	109.2
Disk Storage Estimate (GB)	1000
Data Transfer (USD per GB)	0.02
Total Computing cost (USD)	546
Total Data Transfer Cost (USD)	20
Total HPC Cost (USD)	**566**

*Our estimate uses a quote for Amazon Web Services EC2 OnDemand u-12tb1.112 large compute instance (2x) [43], but HPC prices may vary. Each instance uses 448 CPUs and has a network performance of 100 GB.

A7: Drone Software Memory Requirements Estimation

Drone Software	RAM (MB)
LS-PIV	500
Convolutional Neural Network	1000
Communications	1000
Structure from Motion	18
Total	**2518**

A8: RECOVER Cost Estimation and Comparison

*It should be noted that the current cost calculations were computed using FEMA damage assessment travel costs and costs to deploy personnel to sample floodwater.

** The hexacopter and fixed-wing costs include the costs of communication and water testing components

	Quantity	Cost	Adjusted Cost
Hexacopter	8	7300	58400
Fixed-Wing	6	8000	48000
Bacteria LAMP Device	1	400	400
Comms Infrastructure	1	35000	35000
Ground Control Station	1	42466	42466
Personnel Salary	36	25	900
Per Diem (Lodging and M&IE)	4	75	300
Total			**185466**

Floods (#)	Current Cost (millions USD)	RECOVER Cost (millions USD)
1	0.3	0.185
2	0.6	0.187
3	0.9	0.189
4	1.2	0.191
5	1.5	0.193

A9: RECOVER Recurring Cost Estimation

Recurring Cost	Quantity	Cost	adjusted cost
Personnel Salary	36	25	900
Per Diem (Lodging and M&IE)	4	75	300
HPC	1	566	566
Total recurring costs			**1766**

B1: Total Surveying Time Calculation

We take Hurricane Harvey's impact on the city of Baton Rouge, LA as a case study for estimating our system's survey time. Baton Rouge is a city of roughly 80 mi^2. We approximate the city as a 9-mile x 9-mile square grid. By doing so, we assume that the time each drone takes to change direction mid-flight, as they would when flying in a curved path, is negligible. We assume a swarm of 6 fixed-wing drones flying 33 ft/s straight over the area. We take the ground resolution of each square image to be 0.061 mi^2, as applied in Fonstad et. al.

$$\text{Length of floodplain/ground resolution} = \frac{9\text{ mi}}{1312.3\text{ ft}} = 37\text{ total flyovers}$$

$$\text{Length of floodplain/flight speed} = 9\text{ mi} \times \left(\frac{1}{33\text{ ft/s}}\right) \times \left(\frac{1\text{ min}}{60\text{ s}}\right) = 25\text{ min flight time for single flyover}$$

$$\text{Total flyovers/total \# drones} = \frac{37}{6} =\sim 6.16\text{ flyovers per drone}$$

$$\text{\# flyovers per drone} \times \text{ flight time for single flyover} = \text{total flight time} = 6 \times 25\text{ min} = 150\text{ min or 2.5 hours}$$

$$\text{Model construction time} =\sim 2\text{ hours}$$

$$\text{Total flight time + model construction time} = \text{Total surveying time} = 4.5\text{ hours}$$

$$\text{Total flyovers} \times \text{ length of floodplain} = \text{total distance covered per drone} = 5 \times 9\text{ mi} = 45\text{ mi}$$

B2: Communications Rate for SfM Calculation

We continue using the Baton Rouge flooding case study. A 3840 x 2160 pixel camera takes images that are roughly 18 MB. Our communications rate is 1.25 Gbps = 1250 Mbps for FSO, so 60 images can be sent to the ground station in around 1 second. Given that multiple images of each subgrid area are required for SfM to have a high degree of accuracy, we assume roughly 3 are taken for each subgrid area.

37 flyovers x 37 flyovers = 1369 total image grid spaces
Total grid space × images per space = 1369 × 3 = 4107 total images
Total images/60 images per second /60 seconds =~ 1.14 minutes to send all images

The communications rate for RF is 87 MB/s, which means that roughly 5 images per second can be sent to the ground station.

Total grid space × images per space = 1369 × 3 = 4107 total images
Total images/5 images per second /60 seconds =~ 13.6 minutes to send all images

RECOVER's hybrid communications system suggests that it will take somewhere between 1-13 minutes to send all images from the fixed-wing drones to the GCS, depending on system performance during implementation.

B3: Drone Range Justifications

Now that weight and size are known, an approximation of power consumption and battery life can be completed; this process is vital to understanding the swarm system as it defines the number of needed drones per square mile. Determining a battery life for the fixed-wing UAV is relatively simple, primarily due to its lack of bespoke modifications. It is directly comparable to existing fixed-wing drones like the Volantex Firstar V2, weighing a little lighter at 7 lbs. Apart from the slightly lighter build, the device features similar features to that of the drone described in this analysis. It features a 4.8v 20Ah (~100 Wh) Lithium Polymer battery, allowing a flight time of about 1.5 hours. Similar performance can be achieved with the surveillance drone in question. Due to the fitment of the high-resolution camera and additional processing needs, however, the power drawn by the system may be a little more. The battery capacity will therefore be assumed to be about 150 Wh, approximately maintaining the 1 1⁄2 hour flight time. Now knowing the battery life and speed of the fixed-wing UAV, the total range of the drone is likely around 75 miles (37.5 if returning to GCS) if a cruising speed of 50 mph is assumed.

The hexacopters will need to be fitted with significantly larger batteries due to the presence of additional electronic components, likely requiring more than double the capacity of the fixed-wing UAV. Assuming a battery life of around 350Wh and a consumption close to 300W, the drone can fly for about an hour. Although this number is lower than the fixed-wing UAV, the batteries will be integrated into the system in a way that allows operators to replace batteries seamlessly. Assuming a cruising speed of around 25-30mph, the hexacopter should be able to cover a distance of 25-30 miles (12.5-15 if returning to GCS). Although this number is not particularly large, it can be compensated by adding more UAVs to the swarm system.

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