ROBOT-ASSISTED MEASUREMENT IN DATA-SPARSE REGIONS

BY

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THESIS

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ABSTRACT

This work investigated the use of low-cost robots, small unmanned aerial vehicles (UAVs) and small unmanned surface vehicles (USVs), to assist researchers in environmental data collection in the Arkavathy River Basin in Karnataka, India. In the late 20th century, river flows in the Arkavathy began to decline severely, and Bangalore's dependence on the basin for local water supply shifted while the causes of drying remain unknown. Due to the lack of available data for the region, it is difficult for water management agencies to address the issue of declining surface flows; by collecting critical hydrologic data accurately and efficiently through the use of robots, where data is not available or accessible, local water resources can more easily be managed for the greater Bangalore region.

Three case study sites, including two irrigation tanks and one urban lake, within the Arkavathy basin were selected where unmanned aerial vehicles and unmanned surface vehicles collected data in the form of aerial imagery and bathymetric measurements. The data were further processed into 3D textured surface models and exported as digital elevations models (DEMs) for post-processing in GIS. From the DEMs, topographic and bathymetric maps were created and storage volumes and surface areas are calculated by relating water surface levels to tank bathymetry. The results are stage-storage and stage-surface area relationships for each case study site. These relationships provide valuable information relating to groundwater recharge and streamflow generation. Sensitivity analysis showed that the topographic surface data used in the stage-storage and stage-surface area curves was validated within ± 0.35 meters. By providing these relationships and curves, researchers can further understand hydrologic processes in the Arkavathy River Basin and inform local water management policies.

From these case studies, three formative observations were made, relating to i) interpretation of the data fusion process using information collected from both UAV and USV systems; ii) observations for the human-robot interactions for USV and; iii) field observations for deployment and retrieval in water environments with low accessibility. This work is of interest to hydrologists and geoscientists who can use this methodology to assist in data collection and enhance their understanding of environmental processes.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 Research Question

In the late 20th century, river flows in the Arkavathy River Basin began to decline severely, and the dependence on the basin for local water supply shifted while the causes of drying remain unknown [1]. To effectively manage local water resources, it is critical to understand the drivers behind the changes in river flows, especially the quantification of anthropogenic changes in the watershed via the construction of hundreds of irrigation tanks. By obtaining bathymetry information of irrigation tanks and lakes in this region, local researchers can better understand physical properties of these water environments. The tanks in the Arkavathy largely serve as unmanaged groundwater recharge basins, and by quantifying these storage volumes one can understand groundwater recharge and streamflow. This information will help locals attempting to rejuvenate Bangalore’s urban lakes calculate lake volume, track shoreline development, understand the potential for biological productivity, and quantify sedimentation.

Collecting environmental measurements in extremely data sparse regions such as the Arkavathy Basin is difficult, especially at a temporal frequency that keeps pace with expected human impacts and environmental changes. Currently, satellite imagery and LiDAR are the two standard methods to collect topographic and bathymetric data for this region, but both options are either lacking appropriate resolution or too costly [2]; thus, there is a need for a low-cost, highly mobile platform to collect environmental data in developing, data-sparse regions.

This study proposes a methodology for topographic and bathymetric data collection using small, low-cost robotics platforms to collect important hydrologic information in the Arkavathy watershed around Bangalore, India. Both unmanned aerial vehicles (UAVs) and unmanned surface vehicles (USVs) were used. By collecting critical hydrological data accurately and efficiently where this information is not available or accessible, local water resources can more easily be managed both now and in the future. Additionally, this robot-assisted approach for data gathering will be of interest to civil and environmental engineers, hydrologists, and geoscientists, especially those operating with budget constraints in data sparse regions.

1.2 Why Focus on the Arkavathy River Basin

Before the late 20th century, the Arkavathy River Basin had the capacity to supply Bangalore, a major metropolitan city of over 10 million people in southern India, with all of its municipal water needs [1]. Now, however, Bangalore has shifted nearly its entire dependence to the Cauvery River due to the drying of the Arkavathy [3]. Multiple studies have been conducted to understand the drying of the basin, but to date no conclusions have been reached. The issues related to water supply and management in the Arkavathy are of considerable interest due to the ever increasing population of Bangalore, its surrounding municipalities, and the country of India as a whole, which will undoubtedly stress future water supplies. Understanding the anthropogenic influences on the Arkavathy watershed is critical in assisting mitigation efforts and developing sustainable solutions for managing water resources, and information gathered during this field study will be used to inform local hydrologists on unmapped shallow water environments while improving data-sparseness.

1.3 Why Focus on Small, Unmanned Vehicles

Unmanned vehicles, including USVs and UAVs, are becoming extremely popular for environmental sensing applications for the following reasons: they are low cost compared to manned systems; they are highly versatile and efficient in terms of sensing payload technologies; and they keep humans out of dangerous or harmful environment situations [4,5]. Small unmanned vehicles offer the potential to collect information at high temporal frequencies with the ability to cover large spatial areas. These are critical factors when gathering information in data sparse regions with the goal of improving information availability.

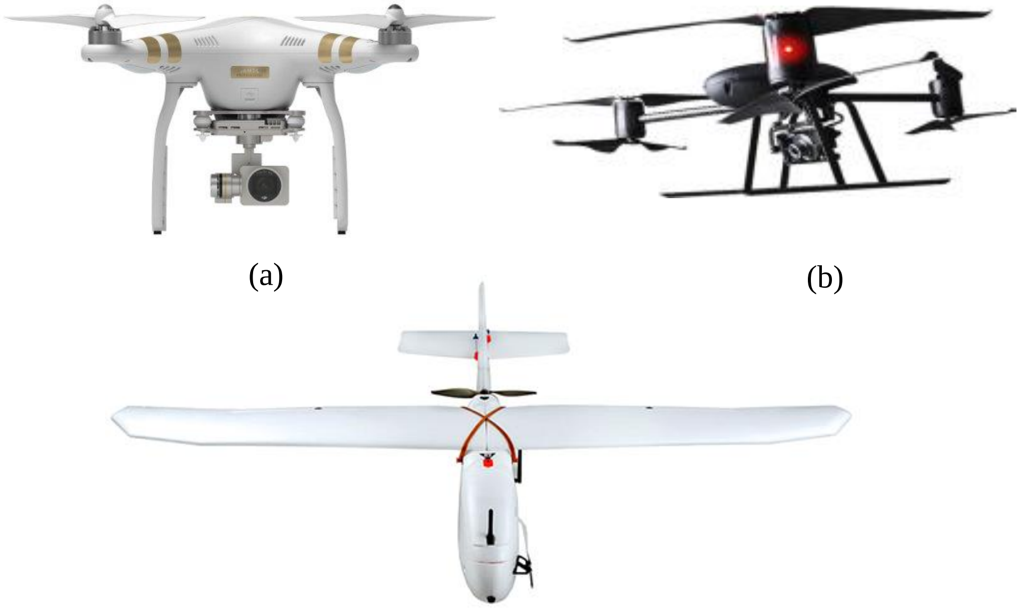
In the Arkavathy watershed, there are three types of environments where unmanned vehicles are ideal for gathering data: irrigation tanks that remain dry outside of monsoon seasons, partially submerged tanks that fill during monsoons, and completely submerged tanks and lakes. To successfully and accurately collect topographic and bathymetric information in all three of these environments within the same time and spatial resolution, using UAVs, USVs, and a combination of both platforms can provide a complete set of measurements.

1.4 Understanding Small, Unmanned Vehicles

Unmanned systems, including UAVs and USVs, have been in use for over 60 years for various environmental, military, and search and rescue purposes [6]. Both of these unmanned platforms remove the operator from the system and allow for diverse methods of remote operation with varying degrees of autonomy [5].

1.4.1 Small Unmanned Aerial Vehicles

Of all UAV systems, small UAVs represent the smallest size, range, altitude, and endurance, and they are the type typically used for environmental sensing applications [7]. Small UAVs allow a human team, which is usually co-located, to remotely navigate and visualize information in environments where humans or other ground-based robots are not practical [7]. In this category, small UAVs are fixed wing or rotary wing types typically up to 2 m in size, can carry a payload up to approximately 2 kg, and, depending on payload weight, can operate for up to 1 hour. There are a wide variety of commercially platforms available; a few examples are shown in Figure 1.1.



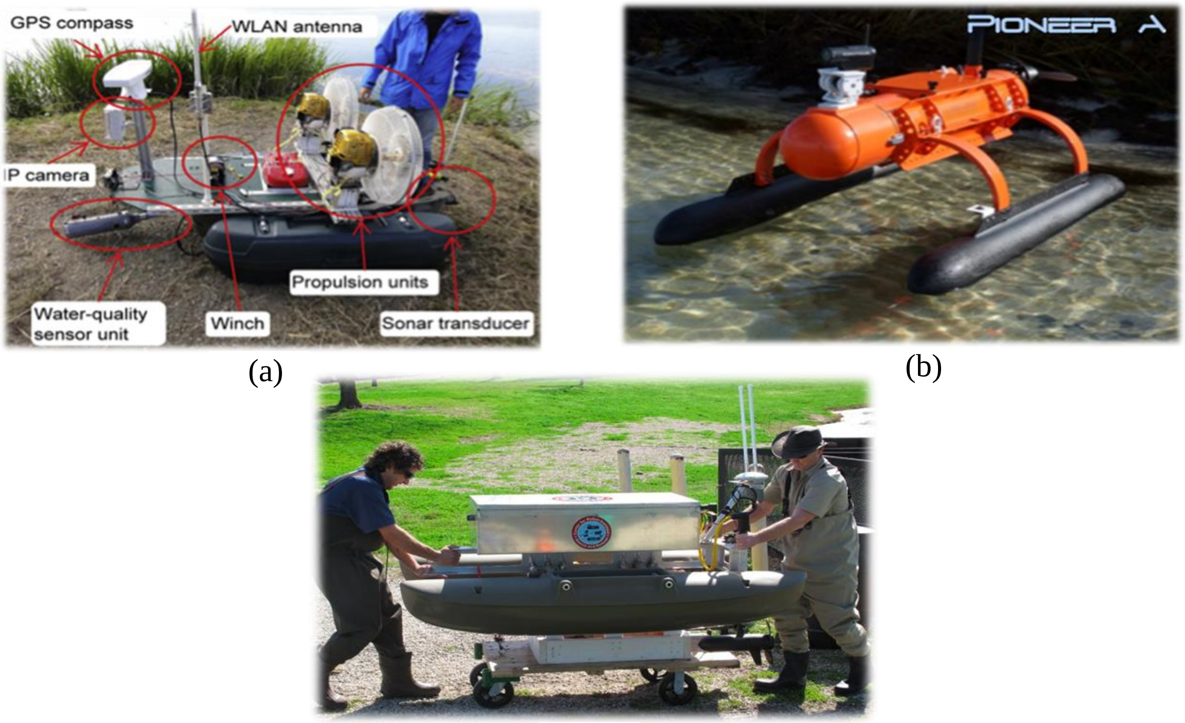
(a) (b)

(c)

Figure 1.1: Various small UAV platforms. (a) DJI Phantom 3: .59m diagonal size, aircraft weight of 1.28 kg, ~10-15 minutes in flight time. (b) Draganflyer X-6: .84 m wide, aircraft weight of ~2kg, can carry up to 335 grams, up to 25 minutes in flight time. (c) 3D Robotics Aero fixed-wing, 1.88 m wingspan, payload capacity of up to 2kg, 40 minutes flight time.

1.4.2 Small Unmanned Surface Vehicles

USVs operate on the surface of the water and are either remotely operated or auto-piloted through radio, Wi-Fi, cellular network, or satellite. USVs take advantage of their air-sea interface to serve as a bridge between heterogeneous air, ground, and marine platforms to introduce new understandings in environmental monitoring, disaster rescue, surveillance, warfare, and defense applications [8]. Small USVs are typically up to 3 m in length, have operational endurances of up to 4 hours, and due to their smaller size are easily deployable in varying water environments [9]. An example of “micro” (< 1.5 min length) and small (< 3 m in length) USV platforms are shown below in Figure 1.2.



(a) (b) (c)

Figure 1.2: Examples of small USV platforms. (a) USV developed by Kaizu (2011), up to 150 kg payload, 1.42 x 1.2 meters in size, 6 hours operation on maximum engine output. (b) The Pioneer, by NjordWorks Inc. 1.07 x 0.64 meters in size, 0.2-1 hour endurance. (c) USV developed by the Center for Robot-Assisted Search & Rescue at Texas A&M University. 1.9 x 1.2 meters in size, 4-6 hour endurance depending on currents.

1.5 Importance to Civil and Environmental Engineering

USVs and UAVs are becoming increasingly popular for various civil and environmental applications. For example: UAVs have been used for terrestrial surveying and monitoring, construction management, and disaster response; USVs have been used for environmental sensing, in-situ sampling, and defense applications. Investigating and developing new uses and sensing applications for both of these platforms are important to improve their use in collecting crucial environmental measurements.

Despite the growing popularity and availability of USVs, platforms that are low-cost, customizable, and highly mobile that can be easily deployed for environmental sensing applications are lacking. This study investigates the use of a custom USV and affordable, commercially available sonar equipment to generate an economical alternative to existing bathymetric surveying platforms.

In landscapes like the Arkavathy Basin that are continually changing due to human intervention, it is important to develop high temporal topographic surveying methods. Inexpensive, commercially available UAVs and imaging sensors provide a viable solution, and this study provides a case study application for the first time in rural Karnataka, India.

When investigating topography of regions that are partially submerged, there is a need to collect and merge topographic data with bathymetry. To the best of the author’s knowledge, no standard platforms or processes exist for this type of data fusion. In this study, a field site is chosen and sub-surface/above-surface measurements are combined to provide complete characterization of an irrigation tank. This type of data collection and processing will be very useful to help answer hydrology-related questions in environments that are constantly changing in the Arkavathy due to periods of heavy rainfall followed by dry periods, and will be applicable to other environmental or geophysical science-related applications.

1.6 Contributions

There are two distinct contributions that come from this thesis regarding the use of small, unmanned systems to assist in environmental measurements in a data-sparse region. Specifically, there is no standard method for integrating topographic and bathymetric information collected on a small-scale using these types of platforms.

1.6.1 Contribution 1

Demonstrate a low cost, multi-robot methodology that can be easily deployed in various water environments to collect topographic and bathymetric measurements. This approach will enable the navigation of previously unmapped water environments and improve information availability in developing, data-sparse regions.

1.6.2 Contribution 2

Demonstration of the fusion of topographic survey data and bathymetric point measurements to characterize partially dry water environments. Two low-cost unmanned vehicles, a USV and UAV, are used to successfully illustrate this concept.

1.7 Organization of This Thesis

This thesis is organized as follows:

- Chapter 2 begins with a thorough literature review of current field robotics applications for both UAVs and USVs, an overview of various topographic mapping methods, and surveying methodologies for generating bathymetric maps.
- Chapter 3 presents a methodology for producing topographic maps with UAVs, gathering bathymetric information with a USV, and fusing these two datasets together to generate a complete picture. The UAV and USV platforms used in this study are also discussed, and descriptions of three field case study sites are given: Hadonahalli tank, Nelamangala Lake, and SM Gollahalli tank.
- Chapter 4 discusses the field implementation at the three sites, including areas surveyed, UAV flight statistics, and field observations.
- Chapter 5 presents the results from both topographic and bathymetric mapping efforts. Stage-storage and stage-surface area relationships for each site are provided.
- Chapter 6 provides formative observations relating to the use of unmanned systems for environmental measurement, and discusses various aspects of the case study field sites.
- Chapter 7 finally presents conclusions in relation to each of the major findings, discusses special considerations, and suggests directions of future work.

CHAPTER 2

LITERATURE REVIEW

The goal of this study is to provide a feasible methodology for collecting and analyzing environmental measurements using low cost unmanned vehicles, specifically unmanned aerial vehicles (UAVs) and unmanned surface vehicles (USVs), in a developing, data-sparse region. This literature review discusses field robotics applications for both unmanned platforms, focusing largely on environmental information gathering. In addition, this section investigates current topographic and bathymetric data gathering techniques not limited to methods using UAVs or USVs.

2.1 Field Robotics-Related Applications for Unmanned Vehicles

2.1.1 UAVs

Unmanned aerial vehicles (UAVs) offer a viable platform for high resolution remote sensing due to their low cost and high flexibility. Small UAVs have been most effective for visual sensing over large areas, typically high-resolution video and image gathering, at varying temporal frequencies; additional work has investigated the use of small UAVs for environmental interaction [7,11]. Due to the flexibility of sensing payloads, a wide range of environmental sensing and investigation applications are possible with UAVs.

In rocky, landslide prone areas, UAVs have been used to generate a time-series analysis of landslide dynamics to monitor active and non-active areas of a landslide site in the Huon valley, Tasmania [12]. UAVs were also used to track the land cover changes of green algae using high resolution imagery over time [13]. For agricultural monitoring, fixed-wing UAV was fitted with a digital camera to successfully capture imagery at predefined waypoints to ensure adequate image overlap in an area in southeast Queensland, Australia [15]. To monitor spatial water variability in a Pino-noir vineyard, high resolution thermal imagery was captured via UAV [16]. This imagery was compiled with canopy temperature information collected from infrared temperature sensors placed on top of well-watered and water-stressed grapevines to calculate the crop-water stress index.

In addition to environmental monitoring, UAVs have been used for surveillance and search and post-disaster rescue. In forest fires, UAVs missions could include surveillance, location, air quality monitoring, dispatching of first aid kits, supporting evacuation of residential areas, guiding personnel to safe zone [17]. In a field test study, search and rescue UAV applications were tested during an operational forest fire [17], illustrating the use of different payload systems and the reduction in risk to search and rescue personnel. UAVs have also been used to detect humans in post-disaster environments via the use of thermal and color imagery [18].

Additionally, UAVs have been used in multiple civil engineering applications, including monitoring construction progress [19], infrastructure health assessment [20], and road pavement health monitoring [21].

2.1.2 USVs

USVs have recently emerged as a viable platform for many marine operations, and are used by academic researchers, government personnel, and corporations [5]. Although there is not an official system for USV classification, the most commonly used descriptions are from the U.S. Navy USV Master Plan. The vehicles mainly focused on in this review are X-Class USVs, vehicles less than 3m in length, and Intermediate Class, vehicles between 3m and 7m, and are typically used for “low-end” intelligence operations, such as surveillance, reconnaissance, and environmental studies [4,9].

The most common uses of USVs are for observation and collection, as well as characterizing the physical environment [22]. A majority of the USV platforms being developed and tested by researchers are used for collecting environmental data. Typical environmental USV payloads include GPS, temperature, pH, chlorophyll A, conductivity, turbidity, mass spectrometers for measurement of volatile organics, and a wireless link for real-time data monitoring [10, 23]. One study completed a multi-parameter sampling campaign with multiple instruments along 20-kilometer stretch of Hillsboro River in Florida [10]. For geospatial analysis of the data, ArcView was used to create contour maps and surface plots for visualization. Another USV platform was developed for environmental monitoring and sea patrol of fish stock survey, coral reef conditions, and water quality in Malaysia with the hopes that the autonomous USV platform would complete these tasks typically performed by Sea Patrol personnel more economically and efficiently [23]. The USV used in this case study was 2.96 meters long, and equipped with GPS, IMU, and a Fish Finder. A series of sea experiments were carried out in Johor, and the USV and onboard sensors performed successfully in monitoring the Malaysian coastline.

At the University of South Florida, researchers have developed a USV platform capable of either autonomous or operator controlled navigation and have deployed it with a multitude of environmental sensing payloads [6]. This USV incorporates commercially available parts to keep costs low. An Intermediate Class USV, the ‘Wave Glider’ from Liquid Robotics, was deployed to characterize a shallow-water sandbank environment where intensive aggregate extraction takes place [24]. Although these vehicles are larger and have the capabilities to navigate through more treacherous water environments with faster surface flows, for the purpose of deployment in areas difficult to access a smaller, more easily mobile platform is desired.

2.2 Topographic and Bathymetric Data Gathering

2.2.1 Topographic Map Generation

The first topographic map produced by the USGS was in 1879, the first year they were established [25].These early maps were created by hand using tape and compass traverses, and a method known as “field sketching” to generate contour lines representing the terrain. Now, however, revolutions in mapping technologies, including survey techniques and instrumentation, satellite data, and aerial imagery, have drastically improved the accuracy, efficiency, and coverage of topographic mapping [25].

One of the more modern methods for generating topographic surveys is mapping the earth from space via satellite imagery. Most mapping in this category is performed using regional satellite imagery, from Landsat, SPOT, or some other low-resolution data set [26]. However, the resolution of these images is often too poor to perform traditional topographic mapping, and most of these projects are concerned with “thematic mapping” of land cover. In more recent years, high resolution satellite imagery (HSRI) is being used to generate more accurate topographic maps. For example, IKONOS, a commercial earth observation satellite, provides high resolution imagery at a resolution of 1m as opposed to Landsat imagery with a resolution of 5m [27].

In addition to satellite imagery, Light Detection and Ranging (LiDAR) is a remote sensing technology that uses light in the form of pulsed lasers that measure ranges [28]. LiDAR systems typically consist of a laser, scanner, and GPS system, and are used with either airplanes or helicopters to survey large areas. LiDAR has been used to characterize terrestrial features, including topographic mapping [29,30], geomorphic features of deep-seated landslides [31], tidal channel geomorphology [32], river environments [33], and streams and forest canopies [34]. LiDAR scanners have also been used to characterize ocean surface topography after completing low-altitude surveys (<300m) with 2D scanners [35].

While LiDAR scanners have the capabilities to generate high resolution data sets, these platforms are typically too expensive for high temporal surveys; thus, small UAVs have emerged as a low-cost alternative that produces similar results at low altitude levels [36-38]. These aerial vehicles can be programmed to fly autonomously in straight line grid-like patterns to ensure optimal digital photo overlap, which are then used in 3D model reconstruction. This methodology has been shown to produce high resolution topographic information for a wide range of terrestrial environments, including glacial areas [39], coastal environments [38], and agricultural watersheds [40]. With the help of computer vision techniques, UAVs have been deployed to produce 2 cm resolution 3D surface models to capture micro-topography of Antarctic moss beds [41], illustrating the wide range and high precision applications for topographic mapping with small unmanned aerial vehicles.

2.2.2 Bathymetric Map Generation

Before the availability of modern surveying technologies, early hydrographic surveyors used a hand-held rope, weighted at one end with a 10-pound piece of lead that a leadsman lowered until it touched bottom, when he would read and record the depth manually. This measure of depth is known as a sounding [42]. Early in the 20th Century the wire drag method was improved, which involved the sweeping of an area with a wire at a preset depth extended between two vessels [42]. This method proved very useful because it identified potential sub-surface hazards for ships.

Modern research efforts have resulted in acoustic technologies, including both single beam and multibeam sonar instrumentation, as the current norm for generating bathymetric data. In ocean environments where the movement of the waves may cause significant error, multibeam echo sounders have been used to correct for the boats movement [43]. To map areas off the southeastern shore of Italy, a multibeam echo sounder collected data over an 800 km^2 area [44]. A cruiser carried four acoustic sounders all operating at different frequencies, all collecting relevant depth information. This work resulted in the identification of displaced sediments, failure scars, and areas of erosion. Another study used multibeam echo sounder to determine the depth of the Marina Trench, one of the deepest parts of the world's oceans [45]. Using multibeam echo sounder, the deepest part of the trench was determined with ± 25 m accuracy.

In smaller water environments, such as lakes, rivers, or estuaries, smaller boats are typically used with highly portable instrumentation. For the past 20 years, the USGS has been conducting bathymetric surveys using various fathometer, or echo sounding, instrumentation [46]. Sonar, satellite imagery, and GPS were used to generate a bathymetric map for Lake Tana in Ethiopia [47]. A commercially available Garmin™ fish finder and a handheld GNSS receiver were chosen to collect depth and horizontal positioning information for their low cost, compactness, and high portability. Another study used a Lowrance Electronics sonar instrument (~US$1,000) with GPS to collect depth information near a coral reef off the Belize coast [48]. In both cases, the collected data were process in ArcGIS to generate bathymetric maps.

In addition to surveying performed on the water's surface, water-penetrating LiDAR green light decomposition algorithms have been developed to determine depths of shallow water environments [49]. Airborne Light Detection and Ranging (LiDAR) is an active remote sensing technique used to acquire 3D representations of objects with very high resolution [50]. For this study, a continuous wavelet transformation (CWT) was applied to two full-waveform LiDAR datasets for the Snake River in Wyoming and the confluence of the Blue and Colorado Rivers in Colorado, which had depths of < 2 m each. The mixed LiDAR signal produced by water surface and water bottom reflections was processed to extract both surface and bottom location with ~3cm accuracy in mostly clear water; however, this method is very limited in terms of applicable water environments.

CHAPTER 3

METHODOLOGY

The proposed approach is described in detail within this chapter. This chapter starts with introductions to the general region of interest and a description of each case study site. Following that, the USV and UAV platforms and equipment setup are described in detail, including the sensors and payloads used. Finally, the workflow for processing the data into topographic and bathymetric maps, and stage-storage and stage-surface area relationships is presented. This includes creating a digital elevation model, spatial calculations performed in a GIS, and surface interpolation.

3.1 Region of Interest

The area of interest for this field study was the Arkavathy River Basin, adjacent to Bangalore City in Karnataka, India (13.0°N, 77.6°E), with a population of approximately 10 million. The watershed in this area is largely flat, with over 85% having gentle slopes of less than 3% [51]. Yearly rainfall averages 900 mm, which occurs mainly during the southeast (June-September) and northeast (October-December) monsoon seasons. The river network in this watershed is punctuated by hundreds of man-made reservoirs that are referred to as “tanks”. These tanks consist of a dam and a land depression. The tanks fill in the monsoon season and used to support agriculture until groundwater displaced their use in the 20th century [52].

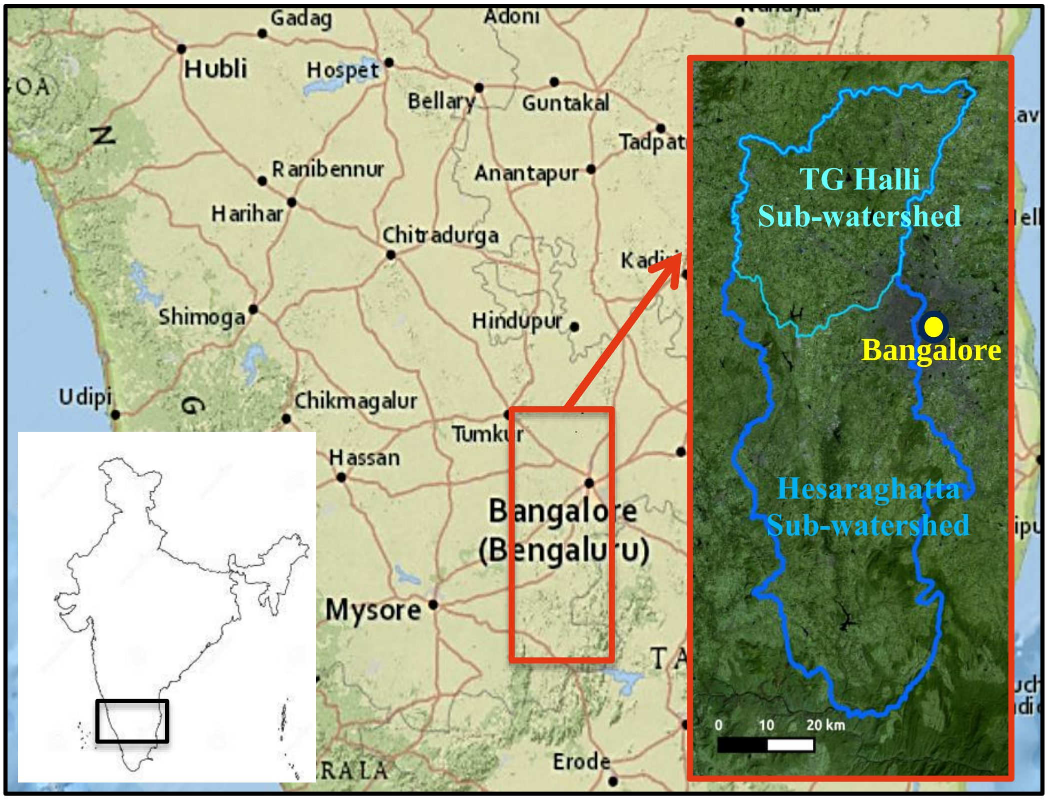


Figure 3.1: Location of the Arkavathy River Basin outlined in red in the state of Karnataka, India. The basin is just west of Bangalore city, and is made up of two sub-water sheds: TG Halli and Hesaraghatta sub-watersheds.

To demonstrate data collection with UAVs, USVs, and a combined approach, three field case study sites within the Arkavathy River Basin have been chosen due to various physical attributes: Hadonahalli tank, Nelamangala Lake, and SM Gollahalli tank. Additionally, these sites are frequently monitored by local researchers, and improving information availability for these locations is more beneficial compared to other potential case study sites. Figure 3.2 shows the locations of each study site relative to Bangalore city.

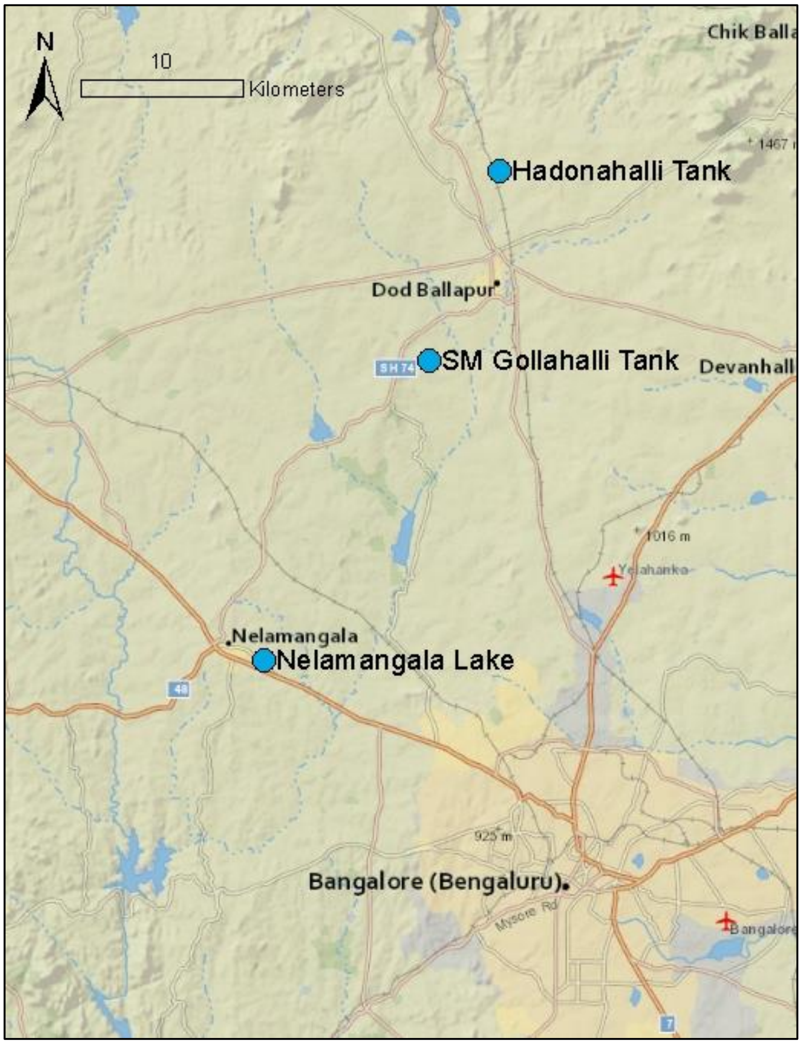


Figure 3.2: Location of the three case study sites: Hadonahalli tank, SM Gollahalli tank, and Nelamangala Lake, all located within 50 km from Bangalore city. These sites are frequently monitored by local researchers, and providing additional measurements at these locations will aid researchers' efforts.

3.2 Field Case Studies

The first area of study was Hadonahalli tank, located about 30 miles north of Bangalore city. This area of this tank surveyed was just over 202,000 m^2, with a total elevation change of approximately 11.5 meters from the lowest to the highest points in the tank. Small pockets and depressions with sharp changes in elevation were prevalent due to locals desilting the area. During the data collection period, this tank remained largely dry with large areas of minimal tree cover, thus Hadonahalli was an ideal candidate for topographic mapping via UAVs.

Figure 3.3: Boundary of Hadonahalli tank surveyed with a UAV. The total area was approximately 202,000 m^2, and had areas of steep elevation changes as well as areas of relatively flat topography. The west end of the tank had medium tree cover, and the east side of the tank was relatively clear of vegetation.

The second case study site was Nelamangala Lake, located in west Bangalore. The total area surveyed with the USV was 8,200 m^2. Parts of the lake were easily accessible as it was surrounded by an access road on the north and east shorelines from which USV deployment took place. Local researchers study this lake and surrounding areas to understand water quantity and quality issues; therefore, the information collected from this lake is of value.

Figure 3.4: Location of Nelamangala Lake. The outline in blue refers to the boundary of the portion of the lake surveyed with a USV, which measured approximately 8,200 m^2. A majority of the west side of the lake was heavily covered in vegetation and was incapable of being navigated through with the USV.

The third area of study is SM Gollahalli irrigation tank, located 25 miles North of Bangalore City. The total area of SM Gollahalli is about 44,000 m^2, with a maximum elevation change of just over 9 meters in the tank. During the data collection period, a large portion of this tank was fully submerged due to the monsoon rains, and a majority of the northeast area of the tank was free of tree cover. At this location a UAV was used to collect topographic information in unsubmerged areas, and the USV platform was deployed to collected depth point readings in the submerged portion.

Figure 3.5: Boundary of SM Gollahalli tank surveyed with a UAV and USV, highlighted in blue. The area surveyed aerially was 44,000 m^2. The middle portion of the tank had dense tree cover; however, this area was generally very flat and important topography changes were not missed with the UAV.

3.3 Equipment and Setup

3.3.1 UAV Platform and Payload

To collect imagery for the generation of topographic maps, the small UAV platform used for this study is the Iris quadcopter by 3D Robotics (3DR). The Iris is equipped with a 3DR uBlox LEA-6 GPS, Radio Telemetry at 915 MHz, and has up to a 1 km radio range. The Iris offers ~10-20 minute flight time depending on payload, and has a payload capacity of 400 g. All hardware, software, and firmware are open-source, including ArduCopter 3.2, a complete UAV platform offering both remote control (RC) and autonomous flight options. The imaging payload used is the Sony ActionCam Mini, which contains a 1/2.3 in-type back-illuminated Exmor R® CMOS sensor and has GPS logging capabilities. A forward-facing mounting bracket is used to attach the ActionCam to the UAV at 60 degrees from horizontal to ensure that sudden changes in elevation were adequately captured.

(a) (b)

Figure 3.6: (a) Iris quadcopter by 3D Robotics. The Iris is 100 mm tall and has a motor-to-motor measurement of 550 mm. It can carry a payload up to 400 g and has a radio range of up to 1km. (b) Remote Control used for both manual and automatic control of the Iris. The radio telemetry operates at 915 MHz.

Mission Planner for Windows, developed by DroneCode, serves as the ground control station for the Iris quadcopter. Each flight grid is carefully pre-planned in Mission Planner to ensure coverage of the entire tank as well as adequate image overlap. Various altitudes, waypoints, speeds, and takeoff/landing points are specified according to the topography and layout of each site. These carefully developed flight plans are then loaded into the Iris, allowing for a fully autonomous flight.

COM4
57600

Distance: 1.9819 km
Prev: 166.21 m AZ: 322
Home: 166.21 m

GEO 13.256086 77.501839 906.73m

Status: loaded tiles

Loaded Plan_2_40m.txt

Home Location
Lat 13.25599
Long 77.504272
Alt (abs) 896

WP Radius 2
Loiter Radius 45
Default Alt 100
Alt Warn 0

	Command	Delay				Lat	Long	Alt	Delete	Up	Down	Grad %	Dist	AZ
14	WAYPOINT	0	0	0	0	13.254037	77.50387	40	X			0.0	86.5	177
15	WAYPOINT	0	0	0	0	13.25481	77.503924	40	X			0.0	86.2	4

Figure 3.7: Mission Planner Software and flight planning interface. Waypoints can be manually entered in a grid-like pattern and loaded into the Iris for a fully automated flight. Mission Planner can also specify various flight parameters, such as ground speed, altitude, takeoff and landing locations, and can task the Iris to perform 360 panoramic turns.

3.3.2 USV Platform and Payload

The vehicle used in this study is a custom micro USV airboat built by Dr. Joshua Peschel and his research group, capable of navigating small tortuous spaces. The USV is 0.5 m in length, can operate with up to a 2.25 kg payload, and is equipped with a 5.8-GHz transmitter capable of sending video, telemetry, and sampling data. Battery life for continuous operation is approximately 4 hours, allowing for long range data collection missions.

To measure depth below the surface, a HawkEye hand-held sonar depth finder was fixed to the USV. This lightweight portable depth finder gives instantaneous depth readings within 2.5 to 99 feet to the nearest .1 foot with ± 5% accuracy. This instrument has a 30 hour continuous-use battery life and is ideal for continual operation with the USV platform. Because the HawkEye does not have data logging capabilities, to capture the readings at various time intervals the same GPS-enabled Sony HDR ActionCam was fixed to the USV (see Figure 3.8). This provided a geotagged depth reading as the USV traversed across various water environments.

Figure 3.8: Setup of the USV airboat, HawkEye sonar depth finder, and Sony ActionCam. A counterweight was required to keep the USV balanced while the HawkEye instrument was fixed to one side in order to remain flat against the top of the water's surface.

3.4 UAV Image Processing Workflow

To produce hydrologically useful information from UAV imagery, the images went through a series of steps to extract and process depth, surface area, and GPS information. First, the images were dewarped and processed in Agisoft PhotoScan to produce a Digital Elevation Model (DEM). Next, the DEM was exported into ArcGIS software capable of intensive geospatial analysis. Within ArcGIS, a series of calculations were performed to calculate storage volumes at various water levels.

3.4.1 Digital Elevation Model Generation

After completing all flight missions, the images collected with the ActionCam went through a fisheye effect removal process. Then, the dewarped images were processed into 3D surface models using Agisoft PhotoScan. To generate a textured 3D surface model, PhotoScan first finds matching points and overlaps the images to build a sparse point cloud model. Then, the program calculates depth information for each camera position and combines this information into a single dense point cloud, while applying aggressive depth filtering. After the dense point cloud is reconstructed, polygonal mesh is generated. From the polygonal mesh stage, the model is exported into a DEM at a maximum effective resolution (as determine by PhotoScan).

3.4.2 Spatial Calculations in GIS

First, the DEM was imported as a raster dataset into ArcMap. All grid cells in the dataset that are not in the boundary of the tank were masked out, and areas of heavy tree cover were filtered and leveled. To determine the leveled elevation of the trees, an average value using 20 data points around the area of tree cover was used

Storage volumes were calculated for various levels within the tank. At each stage value, all grid cells with an elevation higher than the water elevation were masked out and the remaining cells represented the "submerged" area. The quantity of grid cells at each elevation was pulled from the attribute table. This information was used in Equation 3.1 to calculate storage volume:

$$V_i = \sum_{i=1}^{S} A_c * n_i * E_i \tag{3.1}$$

Where:

$V_i =$ total storage volume at stage level S [L^3]
$S =$ stage level, in integer increments ranging from minimum to maximum tank elevation [L]
$A_c =$ spatial area resolution of grid cell [L^2]
$n_i =$ number of grid cells at elevation i [dimensionless]
E_i = elevation value of each cell at stage level i [L]

Similarly, surface area S_i in feet squared was calculated as follows:

$$S_i = \sum_{i=1}^{S} A_c * n_i \tag{3.2}$$

3.5 USV Data Processing

To produce stage-storage and stage-surface area relationships from geotagged depth readings obtained from the USV, the data points were entered into ArcGIS and interpolated and smoothed over the area of interest to generate bathymetry.

3.5.1 Bathymetric Surface Generation

From the recorded images, GPS coordinates were extracted from the EXIF data, and the depth readings manually entered into a dataset. This dataset was imported into ArcGIS for interpolation. The spline method was used for interpolating a bathymetric surface from individual data points. This method is preferred as it ensures the surface passes through each data point while minimizing the overall surface curvature, and can predict ridges and valleys in the data [53]. The result from spline interpolation is a smooth raster surface from which storage and surface area calculations can be performed in a manner identical to 3.3.2

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3.6 UAV and USV Data Fusion

When the area of interest is partially submerged and partially dry, data acquisition is performed with both the UAV and USV. Each dataset is collected separately. The initial processing of the topographic and bathymetric maps are similar as the methods presented Sections 3.3 and 3.4; however, to replace the submerged topographic surfaces with USV measurements, additional manipulations are required. It is important to ensure the spatial resolution in the GIS interpolation settings match the spatial resolution of the DEM generated by UAV data; additionally, the coordinate systems must be identical for the data merging to be successful. If these conditions are met, the interpolated surface from USV data can replace areas in the topographic map that were submerged during the time of photo acquisition.

CHAPTER 4

IMPLEMENTATION

The methodology discussed in Chapter 3 is implemented for all case study sites. To illustrate topographic and bathymetric measurement with unmanned vehicle platforms, data collection campaigns were successfully completed with a UAV at Hadonahalli tank, with a USV at Nelamangala Lake, and with both a UAV and USV at SM Gollahalli tank.

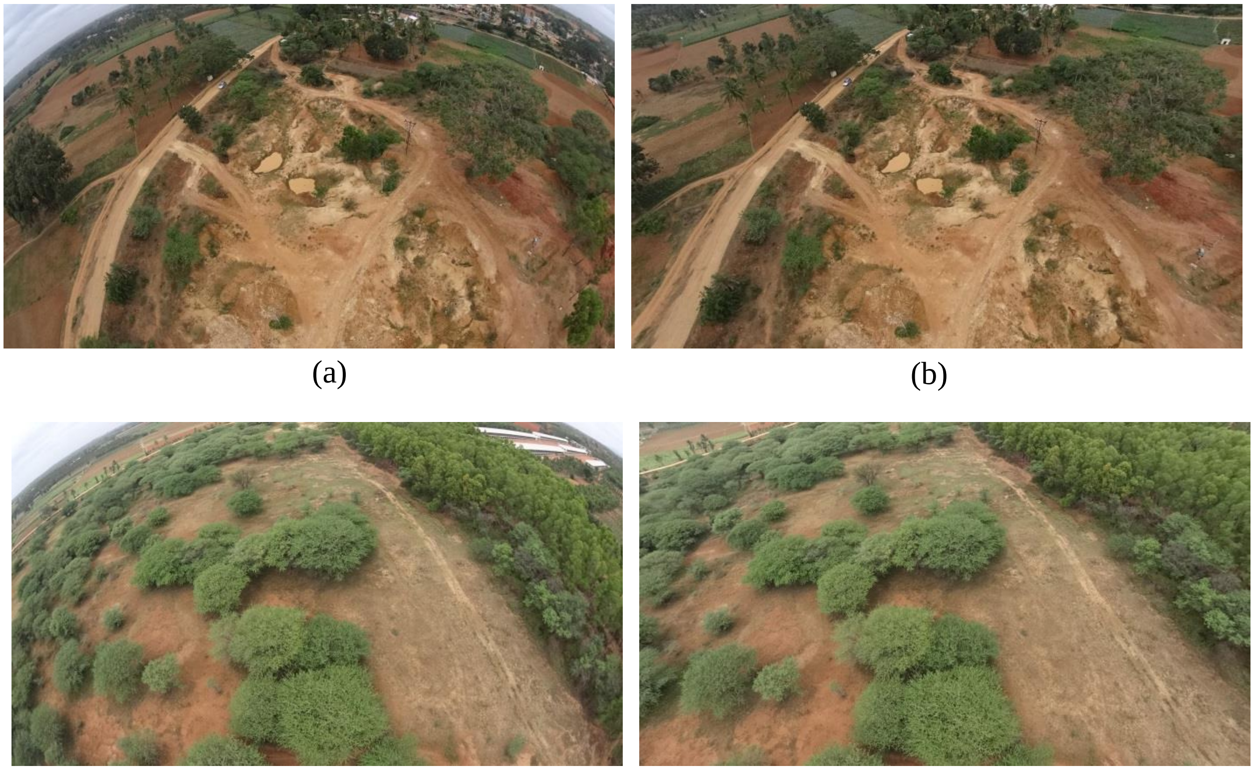
4.1 Field Case Studies

4.1.1 Hadonahalli Tank

To perform a complete survey of Hadonahalli tank, 6 autonomous UAV flights were completed on July 14, 2015 with the flight statistics as listed in Table 4.1, including time of takeoff, total flight duration, average altitude, set speed, number of waypoints reached, and total number of images recorded. The Sony ActionCam was set to record images every 2 seconds to ensure at least 60-80% image overlap for post-processing.

Table 4.1: Flight Statistics for Hadonahalli Tank

Date	Time	Duration	Altitude	Set Speed	# Waypoints	# Images
7-14-2015	08:44 AM	11 min	50 m	5 m/s	15	244
7-14-2015	09:19 AM	10 min	45 m	5 m/s	14	214
7-14-2015	09:52 AM	10 min	35 m	5 m/s	19	218
7-14-2015	10:20 AM	10 min	40 m	5 m/s	16	204
7-14-2015	10:40 AM	6 min	40 m	5 m/s	7	124
7-14-2015	11:00 AM	5 min	40 m	5 m/s	6	118


(a) (b)

(c) (d)

Figure 4.1: Original and dewarped sample images taken at Hadonahalli with the UAV and ActionCam. (a) Original image at 30m altitude with fisheye effect. (b) Dewarped image after removing fisheye effects. Note the many sharp elevation changes and depressions in this area of the tank. (c) Original image at 30 m altitude. (d) Dewarped image. Note the difference in topography of this section that is relatively flat with moderate tree cover.

A total of 639 images with a resolution of 1920 x 1080 pixels were taken with the UAV platform. The fisheye effect, which is inherent to the Sony ActionCam, was removed using GNU Image Manipulation Program (GIMP), an open source image editor. Each image was corrected using the lens distortion tool with a “Main” distortion value of -40%, a “Zoom” value of 5%, and a “Y shift” value of 5%. The dewarped images were then processed in Agisoft, and the processing time was approximately 1.5 hours total. The resulting textured surface model is shown below in Figure 4.2. The DEM exported from this Agisoft model had a spatial resolution of 0.30 meters.

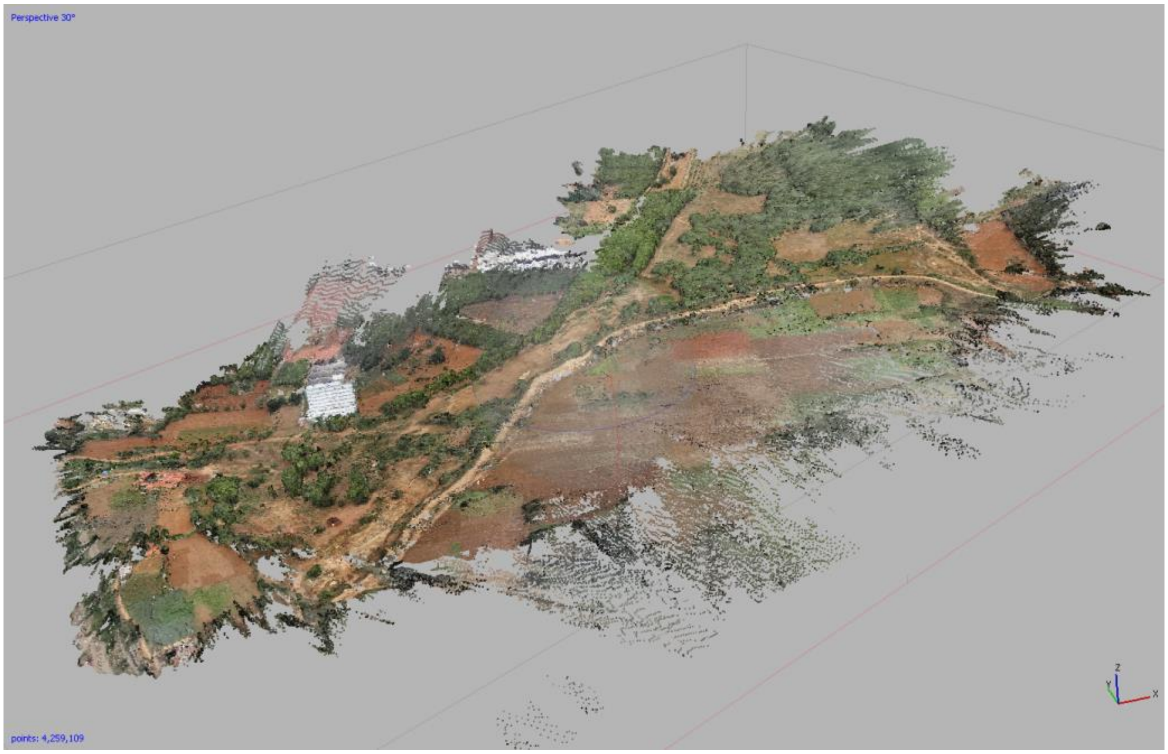


Figure 4.2: 3D textured surface representation of Hadonahalli tank in Agisoft PhotoScan. This textured three-dimensional model is then exported as a Digital Elevation Model for further processing.

4.1.2 Nelamangala Lake

The USV was deployed to collect bathymetric data in Nelamangala Lake. Due to access difficulties (the access road bordered only the northwest and northeast shoreline and most of the south and east areas of the lake were covered by dense, aquatic vegetation) only a portion of the lake was investigated. To gather bathymetric data for the accessible portion of Nelamangala Lake, 2 USV deployments were made on July 30, 2015. The total time it took to collect 816 depth recordings was 28 minutes, covering an area approximately 8,200 m^2. The resulting spatial interpolation model resulted in a resolution of 0.234 meters.

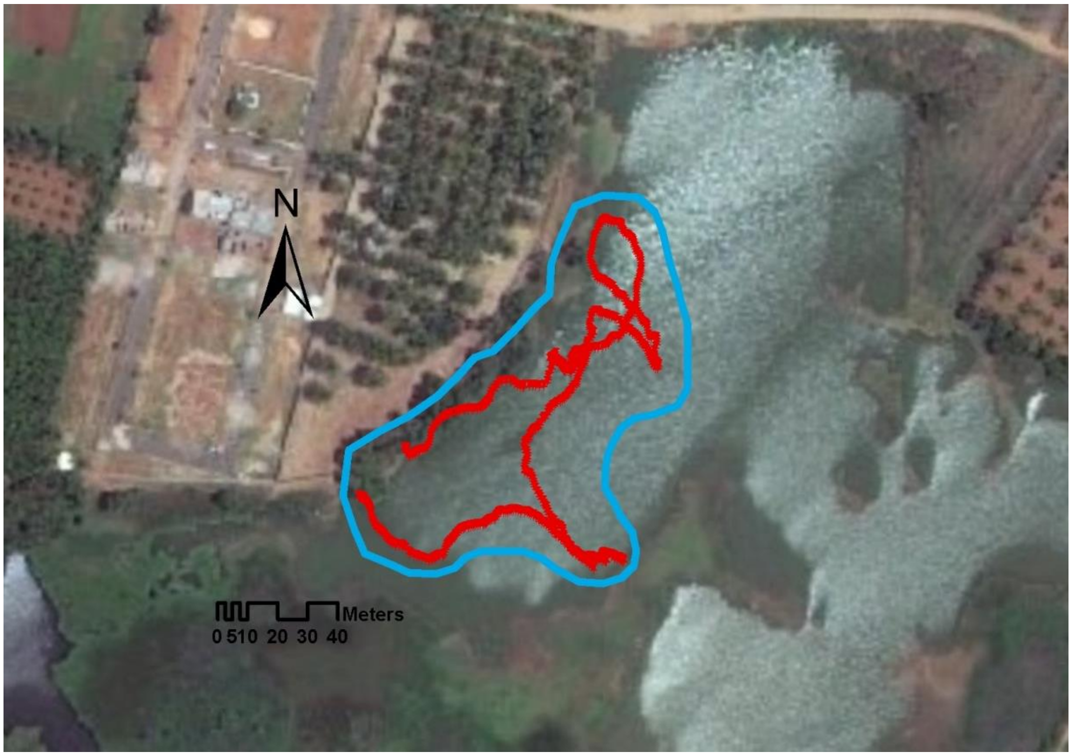


Figure4.3: Visualization of GPS tagged bathymetric photos at Nelamangala Lake. Each red dot represents a photo taken of the HawkEye depth finder reading; an example is shown below in Figure 4.4.

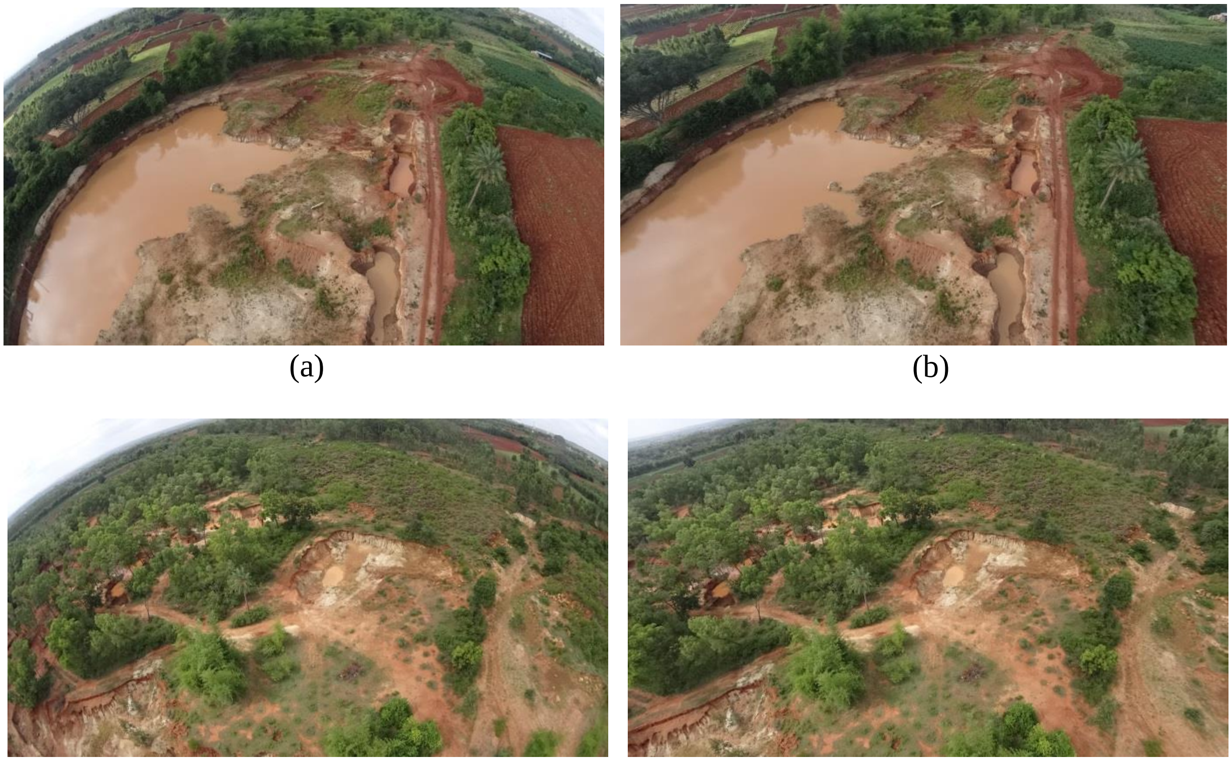
Figure 4.4: Sample image of a HawkEye Depth reading at Nelamangala Lake. The depth reading for each image was manually recorded, stored as a .csv along with extracted GPS information, and imported into GIS for surface interpolation.

4.1.3 SM Gollahalli Tank

To gather aerial imagery at SM Gollahalli tank, 5 autonomous UAV flights were completed on July 3, 2015 with the flight statistics as listed in Table 4.2. The Sony ActionCam was set to record images every 2 seconds.

Table 4.2: Flight Statistics for SM Gollahalli Tank

Date	Time	Duration	Altitude	Set Speed	# Waypoints	# Images Used
7-3-2015	08:16 AM	14 min	30 m	5 m/s	15	268
7-3-2015	08:33 AM	15 min	40 m	5 m/s	14	182
7-3-2015	08:59 AM	10 min	40 m	5 m/s	19	186
7-3-2015	09:13 AM	9 min	40 m	5 m/s	16	178
7-3-2015	09:25 AM	10 min	40 m	5 m/s	7	213


(a) (b)

(c) (d)

Figure 4.5: Original and dewarped sample images taken at SM Gollahalli with the UAV and ActionCam. (a) Original image at 30m altitude with fisheye effect. (b) Dewarped image after removing fisheye effects. (c) Original image at 40 m altitude. (d) Dewarped image.

The 08:16 AM flight differed from the rest and was tasked to be completed at an altitude of 30 meters, rather than 40 meters, to capture the large number of sharp edges and changes in elevation in the topography. After all 5 flights, a total of 447 images were corrected using the GIMP lens distortion tool with a “Main” distortion value of -40%, a “Zoom” value of 5%, and a “Y shift” value of 5%. The dewarped images were then processed in Agisoft, and the processing time was approximately 1 hour total. The resulting DEM for SM Gollahalli with data collected from UAV imagery had a spatial resolution of 0.23 meters.

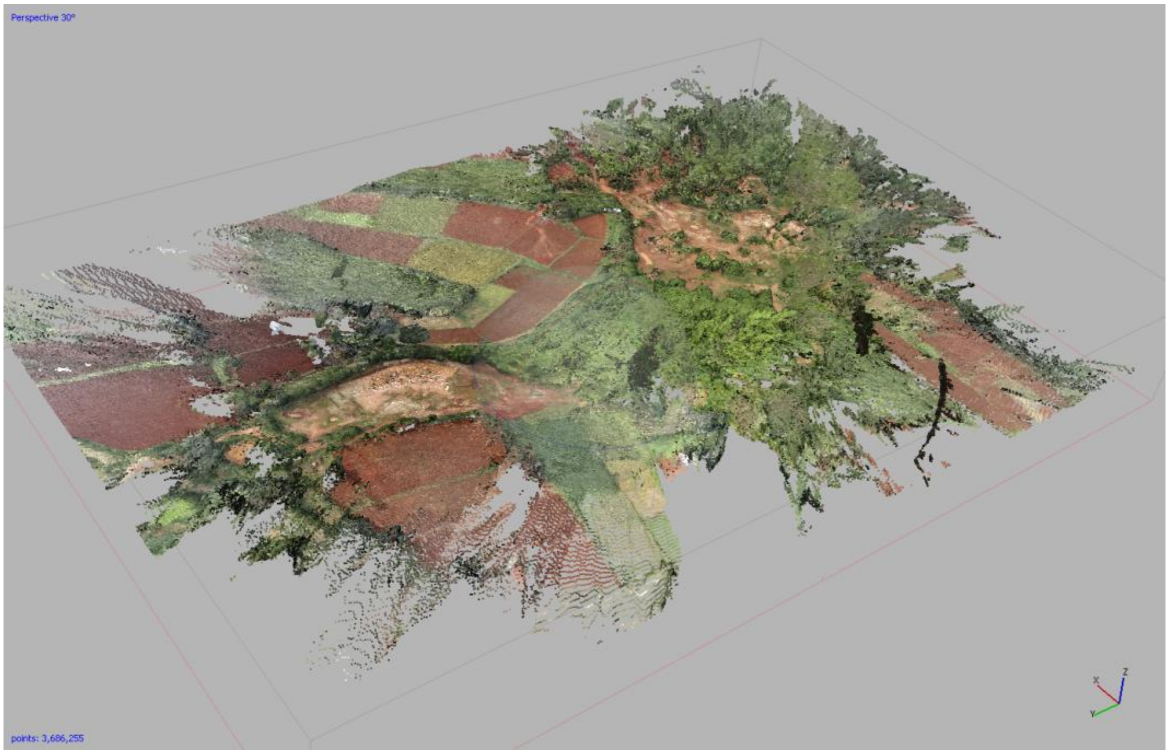


Figure 4.6: 3D textured surface representation of SM Gollahalli tank in Agisoft PhotoScan. This textured three-dimensional model is then exported as a Digital Elevation Model for further processing.

To collect bathymetric information in the submerged areas of SM Gollahalli tank, a single USV deployment occurred (see Figure 4.7). A total of 373 images were collected during a 13 minute USV session. The ActionCam was set up to record an image of the HawkEye depth finder every 2 seconds. The route taken with the USV is shown in Figure 4.8; the submerged portion of the tank was entirely in the northern segment of the tank.

(a)

(b)

Figure 4.7: Field bathymetric surveys at SM Gollahalli tank. (a) Manual operation of the USV around SM Gollahalli collecting depth readings. (b) Deployment and retrieval of the USV at this site occurred without difficulty due to the accessibility of the submerged portion of the tank.

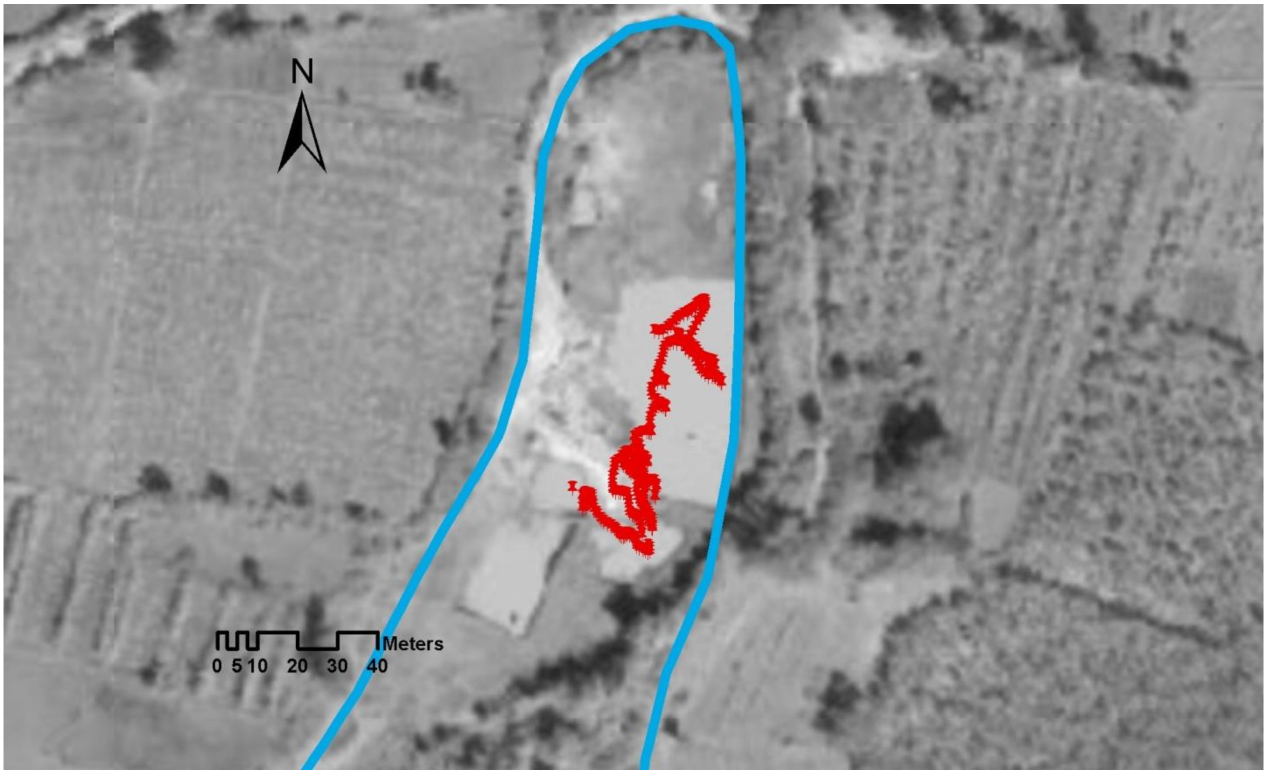


Figure 4.8: Visualization of the GPS tagged bathymetric photos throughout the north end of SM Gollahalli tank. Each red mark represents a photo taken of the HawkEye depth finder reading, shown below in Figure 4.9.

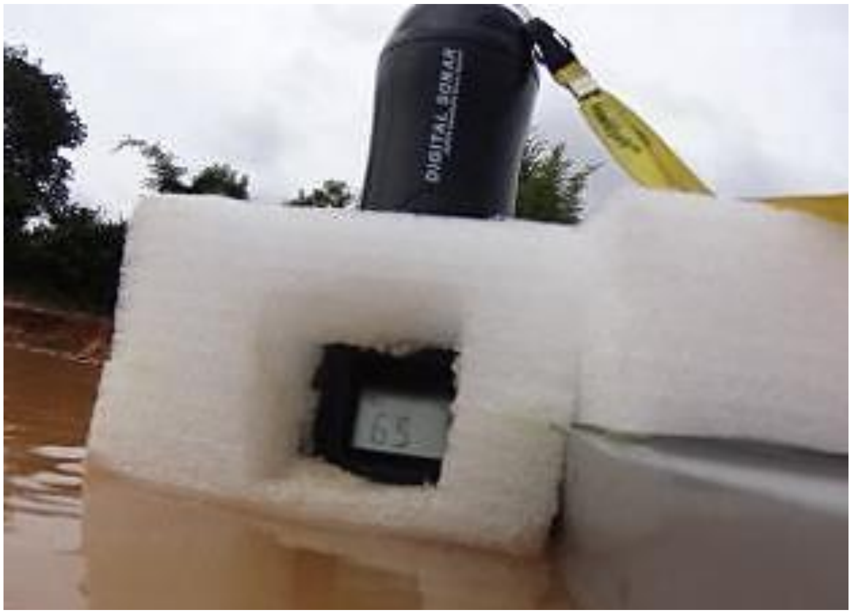


Figure 4.9: Sample image of a HawkEye Depth reading at SM Gollahalli tank. The depth reading for each image was manually recorded, stored as a .csv along with extracted GPS information, and imported into GIS for surface interpolation.

Within ArcGIS, the points collected with the USV were interpolated using the spline method to create a three-dimensional bathymetric surface. To ensure that this surface could merge with and match the spatial resolution to the UAV topographic map, a desired resolution of 0.23 meters was set to match the topographic DEM before interpolation as a setting in the ArcGIS Spline (Spatial Analyst) tool.

CHAPTER 5

RESULTS

The proposed workflow for UAV and USV image processing was tested. For each field study case, stage-storage and stage-surface area curves were produced, and the results for SM Gollahalli were compared to elevation validation points. Topographic and bathymetric contour maps were also created for all three case study sites.

5.1 Hadonahalli Tank

The resulting curves shown in Figures 5.1 and 5.2 illustrate the stage-storage and stage-surface area relationships for Hadonahalli tank. The stage-storage curve nearly conforms to an order 3 power law, with an R^2 value of .98. The two sharp jumps in the stage-surface area curve are largely due to the topography of the tank. Hadonahalli has small areas of steep bathymetry with sharp elevation changes as well as large areas of relatively flat bathymetry. The expansive, flat areas result in large increases in submerged surface area for a relatively small increase in stage. For this tank, there were two areas of heavy tree cover that were leveled out during GIS processing, each corresponding to a jump in the stage-surface area curve.

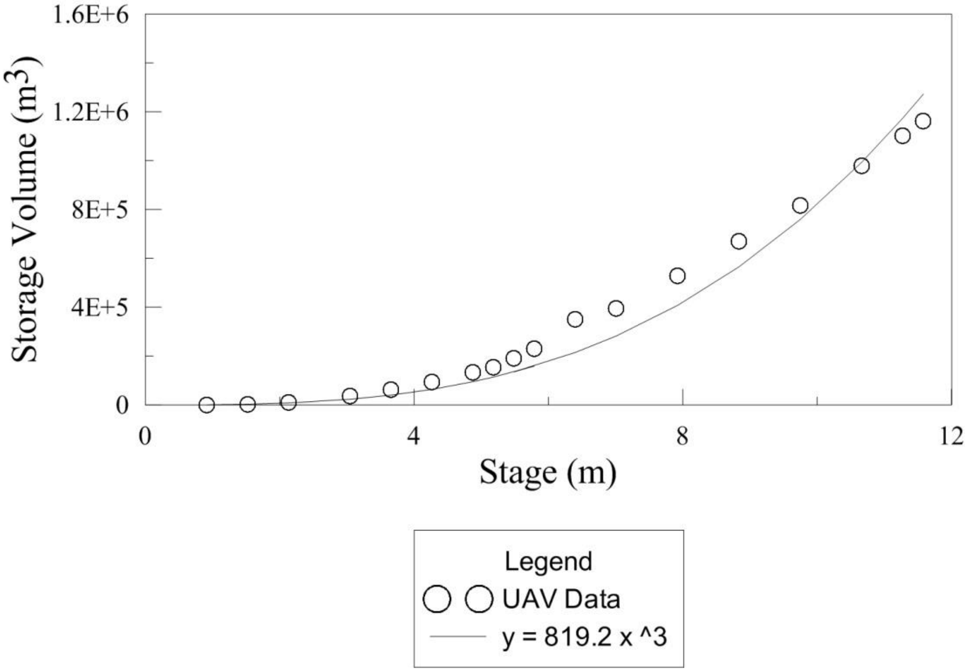


Figure 5.1: Stage- storage volume relationship for Hadonahalli tank and an order 3 power law curve fit. The R^2 value for the curve fit is 0.98.

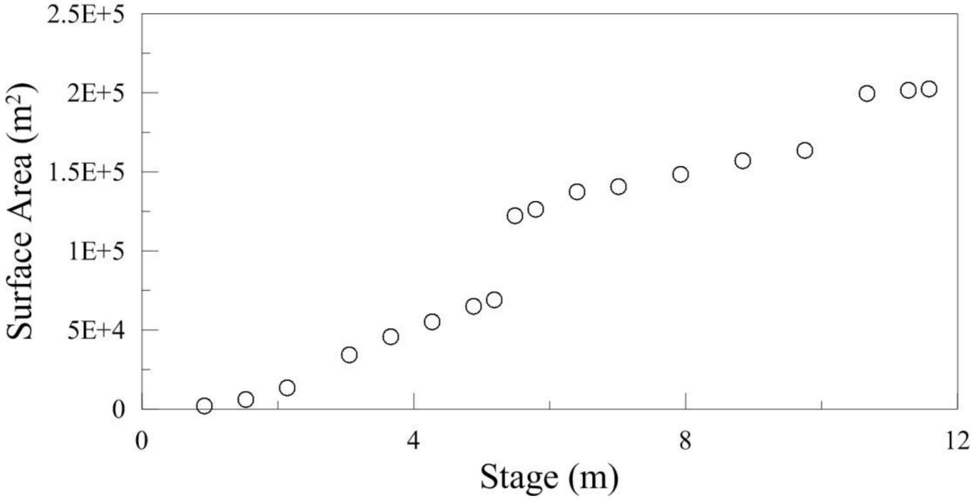


Figure 5.2: Stage-surface area relationship for Hadonahalli tank. The two jumps in the stage-surface area curve are largely due to the topography of the tank and represent the elevations where areas of heavy tree cover had been leveled out.

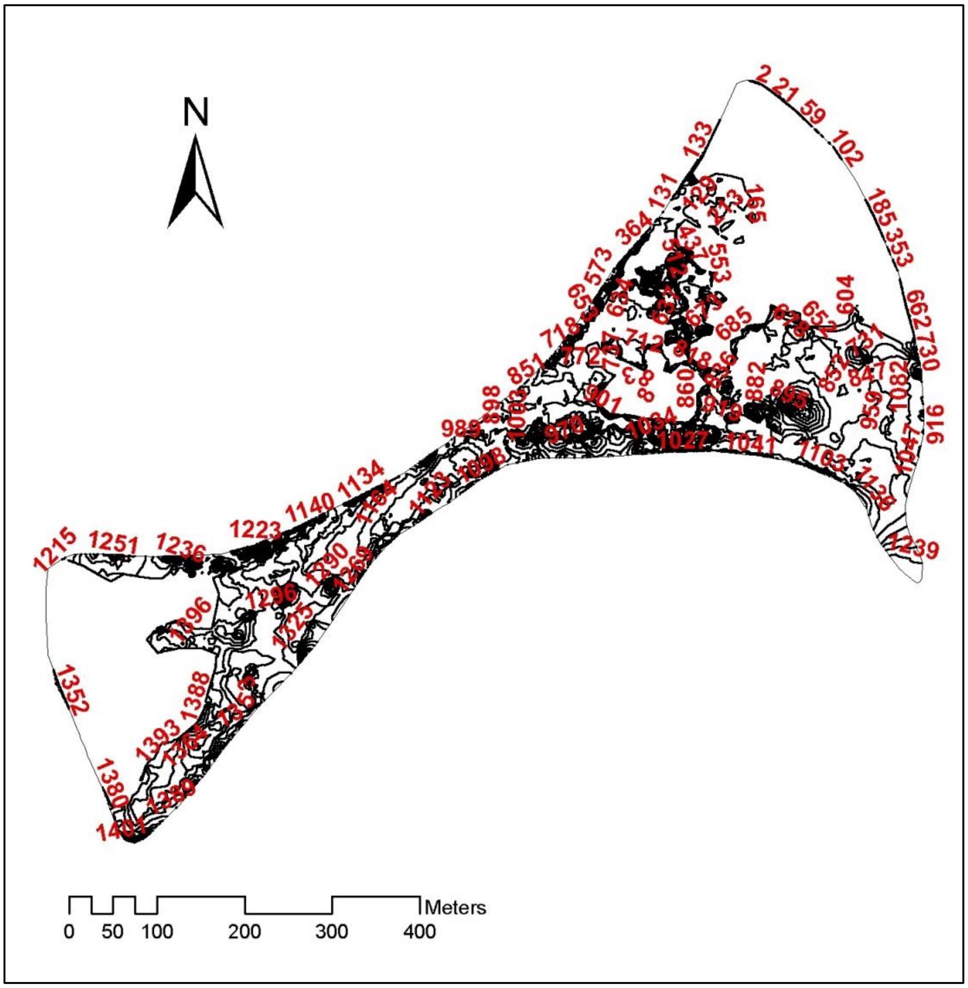


Figure 5.3: Contour representation of Hadonahalli tank. The central areas of the tank had many sharp changes in elevation and small depressions, which are illustrated by the dense contours. The west and east areas of the tank remain relatively flat; this is also where filtering of the trees occurred.

5.2 Nelamangala Lake

The stage-storage and stage-surface area relationships for Nelamangala Lake are shown below in Figures 5.4 and 5.5, respectively. The bathymetry for Nelamangala Lake in the area of investigation had a total elevation change of 3.35 meters. The stage-storage curve nearly fit an order 3 power law, and had an R^2 value of 0.97.

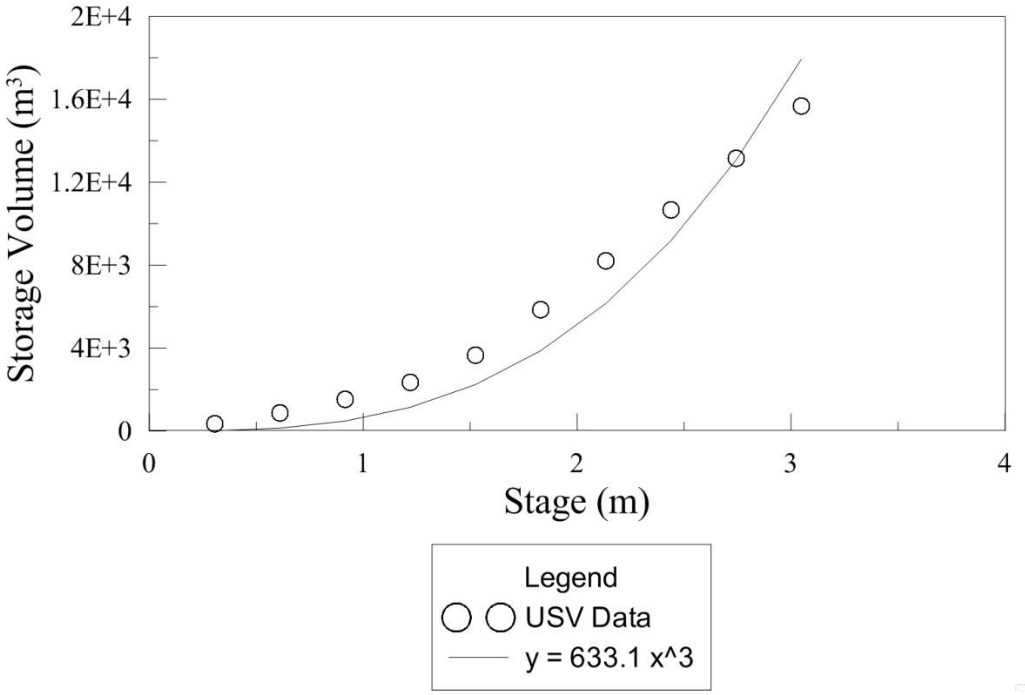


Figure 5.4: Stage- storage volume relationship for Nelamangala Lake and an order 3 power law curve fit. The R^2 value for the curve fit is 0.97.

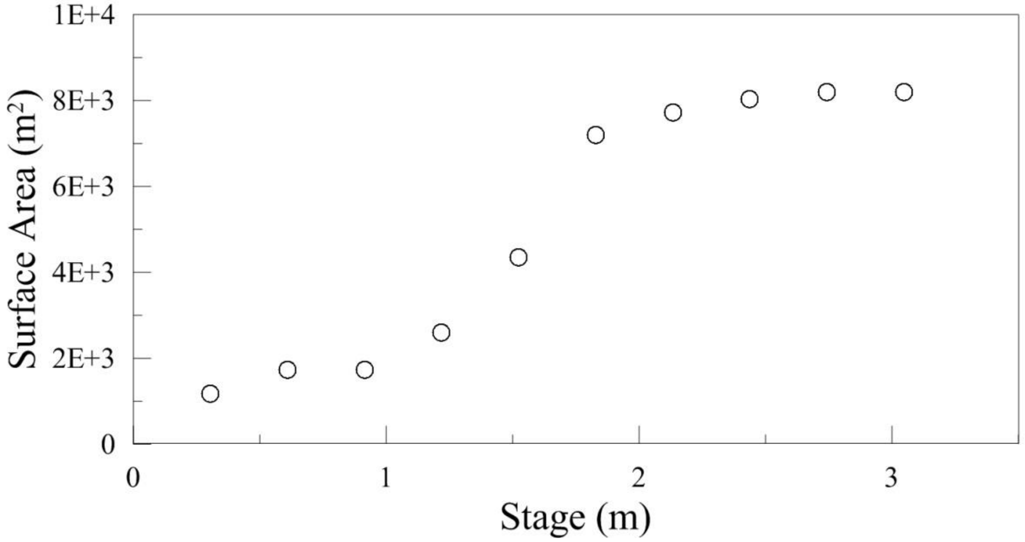


Figure 5.5: Stage- surface area relationship for Nelamangala Lake. At a water elevation of about 1.25 meters and greater the submerged surface area increases at a higher rate.

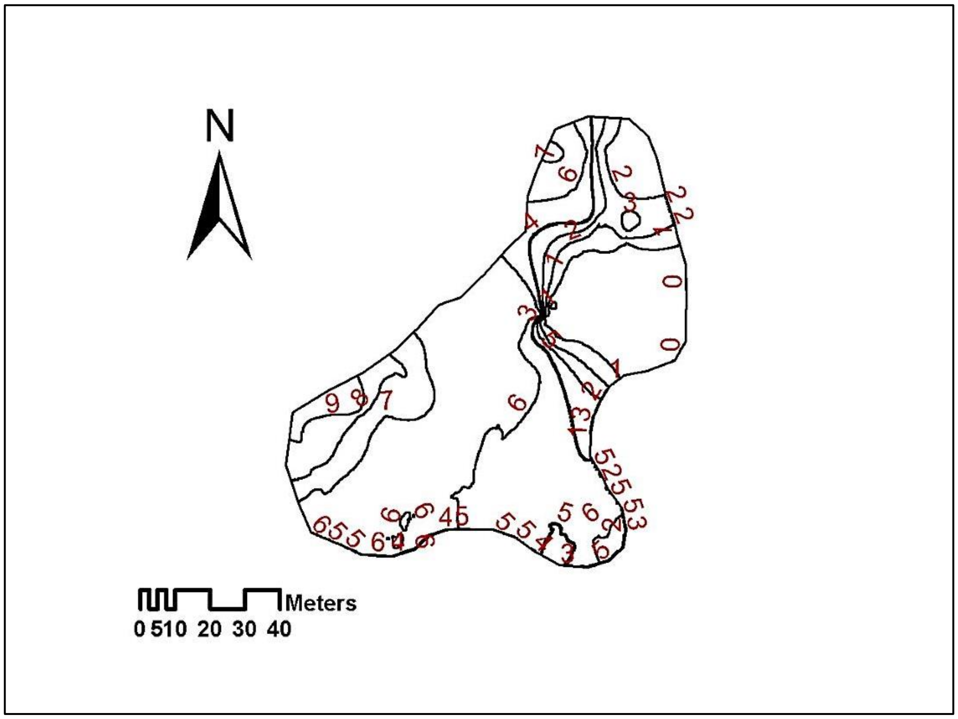


Figure 5.6: Contour representation of Nelamangala Lake. Due to the relatively small elevation change across this area of the lake, the contours produced are less dense compared to the bathymetric contours of Hadonahalli and SM Gollahalli tanks.

5.3 SM Gollahalli Tank

The stage-storage and stage-surface area relationships for SM Gollahalli tank are shown below in Figures 5.7 and 5.8, respectively. The stage-storage curve for the combined UAV and USV data conforms to an order 3 power law with an R^2 value of .99. The sharp jump in the stage-surface area curve is likely for similar reasons as Hadonahalli tank: the topography of the tank has areas of steep elevation changes as well as large areas of relatively flat bathymetry. SM Gollahalli was characterized by a single, flat area of heavy tree cover that was leveled out during GIS processing, which corresponds to the jump in the stage-surface area curve.

As expected, the results from the data fusion approach yield higher storage volume values for a given stage measurement. This is because the storage volume of submerged areas in the tank cannot be captured or quantified with UAV imagery; the supplemental measurements with the USV offer a more complete characterization of the stage -storage relationship in the tank.

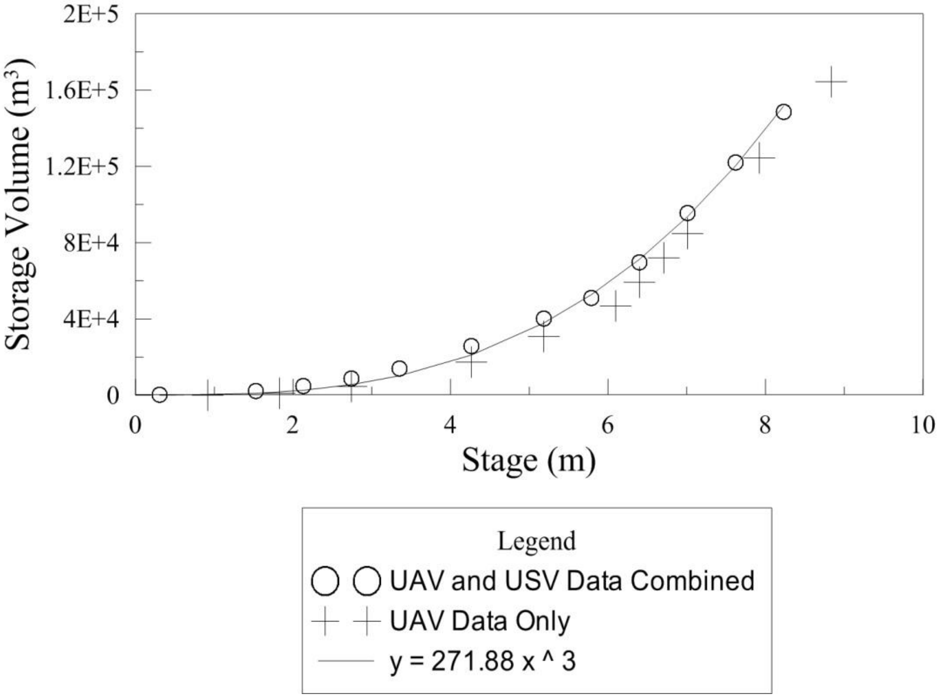


Figure 5.7: Stage-storage volume relationship for SM Gollahalli tank, including the UAV only data, the UAV/USV data fusion results, and an order 3 power law curve fit to the combined UAV/USV curve with an R^2 value of 0.99.

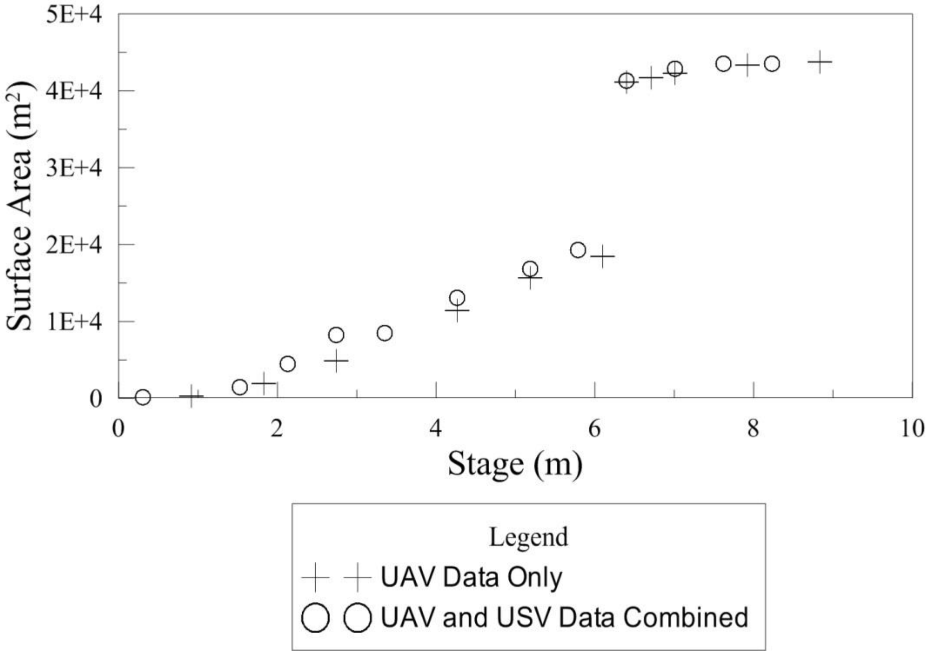


Figure 5.8: Stage-storage volume relationship for SM Gollahalli tank, including the UAV only data and the UAV/USV data fusion results.

Figure 5.9: Contour representation of SM Gollahalli tank. The area of dense contours in the northern section of the tank illustrates the information added via measurement with a USV. The large, flat area in the middle portion of the tank represents the area of heavy tree cover that was filtered out and leveled.

Elevation points were previously collected for SM Gollahalli tank and were used for validation of the resulting bathymetry and stage-storage curve. The data used for validation included elevations of GPS points (numbered 326-345), all referenced to the water level at the time the measurements were taken (point 326). To compare the data, an average of 10 elevation values in the topographic map at each validation GPS point was calculated. Then, the changes in topographic elevation were calculated from the same reference level, point 326, for direct comparison (see Table 5.1).

Table 5.1: Elevation Validation Data for SM Gollahalli Tank (meters)

Validation Elevation Data					UAV Topographic Data		
GPS Waypoint	Back Sight	Intermediate Sight	Reduced Level	Elevation Change	Average Elevation Values	Elevation	Elevation Change
326	2.09			0	901.1658	0	0
325		1.55	0.54	0.54	901.0937	-0.07214	-0.61214
327		1.64	-0.49	0.45	902.0713	0.905457	0.455457
328		1.73	-0.09	0.36	901.6047	0.438904	0.078904
329		1.72	0.01	0.37	901.277	0.111145	-0.25885
330		1.14	0.58	0.95	901.6408	0.474976	-0.47502
331		1.26	-0.12	0.83	902.3843	1.218445	0.388445
332		1.70	-0.44	0.39	900.9762	-0.18964	-0.57964
333		0.98	0.72	1.11	902.6026	1.436768	0.326768
334		0.73	0.25	1.36	902.8209	1.65509	0.29509
336		1.31	-0.58	0.78	902.2946	1.128723	0.348723
337		0.74	0.57	1.35	902.6824	1.516541	0.166541
338		1.24	-0.50	0.85	902.5933	1.427429	0.577429
339		0.68	0.56	1.41	902.8	1.634155	0.224155
340		1.13	-0.45	0.96	902.944	1.778137	0.818137
341		0.59	0.54	1.50	906.7615	5.595642	4.095642
342		0.47	0.12	1.62	903.623	2.457214	0.837214
343		1.53	-1.06	0.56	902.4372	1.271362	0.711362
344		0.98	0.55	1.11	903.1443	1.978516	0.868516
345		1.00	-0.02	1.09	903.386	2.220154	1.130154

The largest deviation in elevation was 4.095642 meters. This is likely because waypoint 341 falls on the edge of a “cliff”, or an area with a sudden, steep change in topography, where the location may correspond to either a low or high elevation. Disregarding this point due to uncertainty, changes in elevation ranged from -.61214 meters to 1.130154 meters. To determine the accuracy at each point in the stage-storage curve, the average change in elevation of all submerged waypoints was calculated (see Table 5.2). For each stage level, the average deviation from the validation elevation points range from -0.34293 to 0.281228 meters; namely, the topography at each stage level is accurate compared to the validation points to within ± 0.35 meters.

Table 5.2: Elevation Validation Data for SM Gollahalli Tank (meters)

Stage	Submerged Waypoints	Change in Elevation	Average Value
5.18	325	-0.61214	
	329	-0.25885	
	332	-0.57964	
	328	0.078904	-0.34293
6.1	325	-0.61214	
	329	-0.25885	
	332	-0.57964	
	328	0.078904	
	327	0.455457	
	343	0.711362	
	336	0.348723	
	330	-0.47502	-0.0414
6.4	325	-0.61214	
	329	-0.25885	
	332	-0.57964	
	328	0.078904	
	327	0.455457	
	343	0.711362	
	336	0.348723	
	330	-0.47502	
	331	0.388445	
	333	0.326768	
	337	0.166541	0.050049
6.71	325	-0.61214	
	329	-0.25885	
	332	-0.57964	
	328	0.078904	
	327	0.455457	
	343	0.711362	
	336	0.348723	
	330	-0.47502	
	331	0.388445	
	333	0.326768	
	337	0.166541	
	340	0.818137	
	345	1.130154	
	334	0.29509	0.199566
7.01	325	-0.61214	
	329	-0.25885	
	332	-0.57964	
	328	0.078904	
	327	0.455457	
	343	0.711362	
	336	0.348723	
	330	-0.47502	
	331	0.388445	
	333	0.326768	
	337	0.166541	
	340	0.818137	
	345	1.130154	
	334	0.29509	
	344	0.868516	0.244162
7.92	325	-0.61214	
	329	-0.25885	
	332	-0.57964	
	328	0.078904	
	327	0.455457	
	343	0.711362	
	336	0.348723	
	330	-0.47502	
	331	0.388445	
	333	0.326768	
	337	0.166541	
	340	0.818137	
	345	1.130154	
	334	0.29509	
	344	0.868516	
	342	0.837214	0.281228

CHAPTER 6

DISCUSSION

In this chapter, the results and performance of the unmanned vehicles used for data collection in this research are discussed in terms of time, ease of implementation, and overall effort. In the end, three formative observations are summarized, which refer to i) interpretation of the data fusion process using information collected from both UAV and USV systems; ii) observations for the human-robot interactions for USV and; iii) field observations for deployment and retrieval in water environments with low accessibility.

6.1 Time Discussion

Field deployment of unmanned systems is often time-sensitive due to weather, battery longevity, and other time-related constraints. It is important that these systems have the capability to cover large surface areas quickly and efficiently, especially in the case study sites presented here; field access for the sites in the Arkavathy was limited to one day at a time because it was difficult to travel to and from these rural areas. The UAV performed quite well under these constraints because of the quick setup time (typically less than 5 minutes). The light weight and mobility of the 3DR Iris enabled the 2-3 person team to navigate around each field site carrying all equipment without difficulty. In addition, 6 Lithium-ion battery packs were used to allow for 6 flights a day, which was enough for complete coverage of the irrigation tanks in the area. The set-up of the USV was also very quick (5 minutes or less), enabling for efficient deployment. The battery life for the USV was up to 2 hours, which enabled the system to navigate around an entire irrigation tank or area of interest within a lake without changing batteries, and 2 batteries were used to very nearly eliminate battery life as a time constraint for USV operation. As the field sites were fairly small, battery life constraints were never an issue.

6.2 Ease of Implementation Discussion

Finding suitable takeoff and landing areas that are clear of foliage and adequately flat was the largest challenge in terms of UAV implementation. Also, it was important to operate the UAV at high enough altitudes to clear the tree line (this was a factor for image clarity and resolution rather than a major barrier to successful implementation). Deployment of the USV system in the field study areas proved to be successful and unchallenging when the depth requirements of the sonar instrumentation were met, and where access pathways or roads were available to get close enough to the water, such as in SM Gollahalli tank. However, at Nelamangala Lake where access was limited, USV implementation throughout the entire lake was not as feasible. However, the air propeller vessel did allow for smooth navigation through shallow and slightly obstructed water environments, including all irrigation tank and urban lake sites investigated.

6.3 Overall Effort Discussion

Topographic and bathymetric surveys of these water environments are ideally performed at high temporal frequencies, thus it would ideally require an unmanned system that takes little to no effort for field deployment. For planning UAV autonomous missions, the Mission Planner software is intuitive and user-friendly, and flights can be planned ahead of time or easily manipulated in the field requiring minimal effort. Both systems, including imaging payloads, the robot platform itself, and controllers, are small, compact, and easily transportable from site to site. The data collected for both platforms included geotagged images from a single camera resulting in straightforward data management and storage. Overall, the transport, management, and storage of the unmanned systems and their data are low-effort and suitable for high temporal frequency deployments in rural, data-sparse areas.

6.4 Formative Observations

After collecting topographic and bathymetric information, the fusion of these two datasets was quite laborious and time consuming. The creation of a single, cohesive analysis tool would significantly streamline this process. Observations for areas of improvement upon the human-robot interaction (HRI) for USVs would significantly improve the systems overall performance, because there are currently no standard human roles present in the literature for unmanned surface vehicle applications [53]. Finally, field observations relating to accessibility do not enable the safe or successful deployment and retrieval of unmanned systems. Developing an apparatus or system that enables deployment and retrieval of unmanned vehicles in difficult environments will enable more efficient data collection in a majority of water environments.

6.4.1 Interpretation of the Data Fusion Process

Collecting information from UAVs and USVs separately requires the fusion of these two datasets to generate a physical characterization of each site. After manually processing and merging the topographic and bathymetric maps, it is clear that the data fusion process is laborious and not suitable for processing on a large scale. In addition, there is no standard, automated workflow for the generation of stage-storage or stage-surface area curves. It is necessary to improve this workflow efficiency via the development of a single cohesive analysis tool for sense-making. A more automated, streamlined process for sense-making with heterogeneous datasets that is not laborious will improve the data science and data processing portion of this case study.

6.4.2 Observations for the Human-Robot Interaction for USV

When operating the USVs in the field, many factors can affect or limit its performance; including but not limited to obstructions to line-of-sight vision and navigation of the robot if there is no video feed, physical obstacles in the water that may not be visible from shore, unknown battery health or sensor performance, etc. Improving upon the human-robot interaction for this type of USV field application would increase the operational efficiency of the custom USV platform used. By exploring various human-robot interfaces, such as the inclusion of visual navigation, sensor/payload feedback, or a battery life monitor, will enable the navigation of this USV platform in areas out of line of sight and enhance human situation awareness.

6.4.3 Field Observations Relating to USV Deployment and Retrieval

The successful deployment of the USV system requires a suitable point of access close enough to the shore to allow for the placement and retrieval of the robot. For small irrigation tanks, this was not an issue or barrier for USV use. However, for other water environments, shoreline access was minimal, leaving areas of the water body unobservable with the USV due to line of sight operational restrictions. To improve the accessibility of these areas of the lake, a type of deployment apparatus, such as a floating case, and a retrieval system, such as a tether to reel in the robot, can be developed. Physically taking the USV out of the water is quite often more difficult than placing it in the water, so even if deployment is not difficult, eliminating retrieval issues is especially critical for dangerous or unsafe environments.

CHAPTER 7

CONCLUSION

7.1 Summary

Collecting environmental measurements in extremely data sparse regions such as the Arkavathy Basin is difficult, especially at a temporal frequency that keeps pace with expected human impacts and environmental changes. Currently, satellite imagery and LiDAR are two standard methods to collect topographic and bathymetric information, but both options are either of too low resolution or too costly. The use of small unmanned systems in this study aimed to fill the need for low-cost, highly mobile platforms to collect environmental data in rural Karnataka. By collecting critical hydrological data accurately and efficiently where this information is not available, local water resources can more easily be managed both now and in the future. Additionally, this work is of interest to hydrologists and geoscientists who can use this methodology to assist in data collection and enhance their understanding of environmental processes.

Field investigations determined that unmanned vehicles, specifically unmanned aerial and unmanned surface vehicles, are suitable platforms for collecting topographic and bathymetric information in a rural, data-sparse region in India. Three locations in the Arkavathy River Basin serve as case studies for data collection with UAVs, USVs, and a combination of both platforms. Stage-storage and stage-surface area relationships were found for each case study, and topographic and bathymetric maps were created for each site as well. Three important formative observations were made regarding using UAVs and USVs for environmental measurement, including: i) interpretation of the data fusion workflow; ii) observations of the human-robot interaction for USV; and iii) field observations to help improve USV deployment and retrieval in inaccessible water environments.

The data fusion approach between UAV and USV observations is lacking an automated, streamlined sense-making process. The current method for fusing the two data sets is very laborious an inefficient; therefore, improving upon the data processing workflow is critical to perform this type of data collection on a large-scale. This will be important for local researchers in the Arkavathy and other developing areas when using unmanned systems at high temporal frequencies in order to keep pace with processing and analyzing captured data.

Aspects of human-robot interaction for USVs in rural water environments is lacking, largely due to the fact that HRI is not well documented or developed for small unmanned surface vehicles. The exploration of various human-robot interfaces can improve USV mission efficiency and situation awareness. This is important for the USV operator so they can monitor the surrounding environment, respond to sensor or vehicle feedback, and gather the information required in the field during time-sensitive operations.

In the field, accessing certain water environments with unmanned vehicles can be difficult or dangerous. Even if USV deployment is simple, retrieval can be a very difficult task, especially in a situation when emergency retrieval becomes necessary. Developing an automated deployment and retrieval system will be important in removing a human operator from dangerous situations and improving accessibility. When these challenges are overcome, spatial and temporal coverage of data collection will improve, as well as researcher safety.

7.2 Special Considerations

There are two important considerations for this work. First, the spatial accuracy and resolution of the topographic and bathymetric maps are dependent on and limited to the GPS sensors used. For UAV mapping, the ActionCam recorded latitude and longitude locations with a standard GPS, which can reliably get 3 meter accuracy [54]. This was suitable for the large areas surveyed in this study. In smaller areas where changes in topography and elevation are very steep and sharp, it may be more important to know the precise relative location of points rather than their absolute coordinates. In this case, relative localization with more precise sensors may be a more suitable option. However, it is still required to collect absolute GPS information for reference.

Second, the bathymetric map generated from the USV data points is limited to the accuracy of the interpolation performed in GIS. Within ArcGIS there are many different interpolation options offered, including but not limited to Inverse Distance Weighted, Kriging, Natural Neighbor, and Spline. For this work, the spline method was used because it generates a smooth surface and passes through all of the data points collected; however, the resulting map may have different minimum and maximum values than the data set and the functions are highly sensitive to outliers [55]. If there is greatly varying bathymetry, the surface resulting from spline interpolation may not be as accurate compared to other methods. It is possible to interpolate using multiple methods and then compare the results; however, there is no way to determine which method gives the most accurate surface because true bathymetry is unavailable for validation.

7.3 Future Work

There are a few areas for additional study. Firstly, the unmanned systems used for environmental measurement for these three case studies can be used to monitor a greater number of irrigation tanks and lakes in Arkavathy River Basin. A large-scale goal of this project is to improve the understanding of the Arkavathy watershed, including flow generation, recharge, and catchment water balance. By quantifying storage capacities of additional water bodies in the Arkavathy, local researchers will be able to understand these watershed mechanisms in greater depth. Secondly, researchers can use these platforms at a higher temporal frequency in the same bodies of water to understand changes in bathymetry and topography over time. Locals visit the irrigation tanks quite often to desilt and remove soil, potentially changing storage capacity. Also, factors affecting life times of lakes include sedimentation and water withdrawal rates, which are important variables to track over time. Thirdly, the USV sensing payloads can be adapted to improve environmental monitoring; for example, using pH, temperature, dissolved oxygen, or conductivity sensors. Monitoring water quality in lakes around the urban fringe of Bangalore can help address important health issues, track potential point and non-point sources of pollutants, and inform local policy on water quality standards.

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