DEVELOPMENT OF A LOW-COST WATER LEVEL GAUGE

BEng Civil Engineering AR30315
Department of Architecture and Civil Engineering

Joe Badger

Academic Supervisor: Dr Chris Blenkinsopp

ABSTRACT

This research paper aims to investigate the potential for low-cost water level gauges and compare their accuracy to similar existing gauges. The water level of rivers and oceans must be monitored due to their unpredictable fluctuations, and their potential to cause serious damage to infrastructure and the environment. An exploration of current designs showed that most river and tide gauges are either very expensive or require readings to be taken manually. Previous research has investigated the possibility of using cameras to monitor different elements of the environment. It has been proven that the use of image processing is an appropriate technique to extract data from environmental images, therefore, this will be the foundation of this study.

The research aims to design an alternative water level gauge, which is low-cost and of similar accuracy to existing solutions. The desire for it to be low-cost is so that it could be used as part of a citizen science project, which would allow for data to be collected in more locations around the UK. Therefore, the design must also be relatively simple to put together and easy to set up. However, the accuracy of the device is crucial and must aim to be accurate to within roughly 1cm of the true depth.

This study examines two possible designs for water level gauges: a camera-based gauge that uses image processing, and an ultrasonic sensor. The camera-based gauge was designed using an ESP32-CAM and ESP32-CAM-MB to make a microcontroller with a built-in camera. This was configured to take photos every 15 minutes, which could be passed through image processing software to determine the depth of a river. The software that was built for this study was written in Python and uses edge detection algorithms to find the distance between the waterline and a reference line. An ultrasonic sensor connected to an Arduino was also used as a water level gauge. The sensor measured the distance from the gauge to the surface of the water, so the change in level could be monitored. Both devices were powered by batteries and saved the collected data to microSD cards. The ESP32-CAM was tested on Brislington Brook for three days and the ultrasonic sensor was tested for six days on the river Avon at Bath Destructor Bridge, and for a single day at Leith Docks in Edinburgh.

The results of the testing found that both gauges produced accurate readings and had error values that were close to the targeted value. Although the ESP32-CAM was relatively accurate during the day, it had the restriction of not being able to collect any data outside of daylight hours. It also had a drop off in accuracy throughout periods of the day due to changing lighting conditions. The ultrasonic sensor produced accurate results when tested on the river, however, had a slightly larger error value when tested on the ocean, due to waves and turbulent water.

This study concludes that both gauges would be suitable alternatives for existing water level gauges. The ultrasonic sensor was highlighted as being the more appropriate design, due to the restrictions of the ESP32-CAM. Further research should be conducted into improving the quality of the camera on the ESP32-CAM, as well as investigating the possibility of using an infrared camera, to be able to capture images at night. The ultrasonic gauge could also be improved with the incorporation of a digital spirit level, and a more expensive ultrasonic sensor with a greater range.

ACKNOWLEDGEMENTS

The author of this research would like to give thanks to the following people for their input and assistance.

University of Bath

Dr Chris Blenkinsopp, Academic Supervisor

Neil Price, Technical Supervisor

Miles Chambers, Woodwork Technician

Steven Handley, Woodwork Technician

Welsh Coastal Monitoring Centre

Gywn Nelson, Programme Manager

William Russel, Coastal Process Scientist

Finally, the author would like to thank their friends and family, whose support and patience is appreciated always.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Water levels in rivers and oceans are constantly changing and can have drastic implications for the environment and society. Flooding can cause severe damage to infrastructure and communities and is very common in the UK. Figure 1 shows the effects of a flooded river on housing in Ironbridge. It is vital that changing water levels are monitored vigorously to limit their potential impact.

Figure 1 - River Severn flooded (BBC, 2022)

The purpose of this research is to investigate the possibility of using low-cost water level gauges and compare the accuracy of their measurements to existing gauges. Two designs are considered in this study. Firstly, a camera-based gauge, which will use image processing, and secondly, an ultrasonic sensor, which will use time of flight principles.

A review of relevant literature examines the importance of monitoring the change in water levels, and the factors driving the change within rivers and the ocean. The significance of citizen science is also discussed, as this research aims to design a water level gauge that is affordable and easy to operate for anyone. Examples of existing research on optical methods for environmental monitoring were explored. Finally, an in-depth analysis of the theory of image processing was also conducted.

Section 3 of this paper details the apparatus used, and section 4 describes the methodology. The methodology has been broken down into three sub-sections: site selection, data collection, and data processing.

The results from the testing of the gauges are displayed in section 5, and an analysis of their effectiveness is discussed in section 6. The discussion examines the accuracy and error of the gauges and analyses the effect that lighting conditions and the time of day have on the results.

The conclusions of this paper are summarised in section 7, before finally, a description of how this research could be continued and improved is outlined in section 8.

2. LITERATURE REVIEW

2.1 Introduction:

Precise measurements of water levels from tide and river gauges help to forecast potential coastal erosion and the effects caused by storm flooding. This project will aim to design and test the quality of two low-cost water level gauges and compare the results to existing pressure transducers. This will be achieved through image processing, using an off-grid camera, as well as an Arduino-operated ultrasonic sensor, to create accurate and automatic water level gauges.

2.2 Importance of water level data in rivers and oceans:

The UK has the most extensive water level record in the world, dating back to 1813 from data collected at the River Tyne (Hogarth et al., 2021). The data collected from water level gauges benefit many industries such as fishing and trade, as it helps with navigation at sea and in harbours and ports (US Department of Commerce, 2017). They are also crucial for monitoring flood plains and rising sea levels due to climate change, and in many countries, they are used to control water usage in areas that experience drought (World Bank, 2022). Although, many areas of the UK coastline and rivers are not monitored at all by existing tide and river gauges. This is because of two fundamental restrictions; they are either too expensive for non-critical areas that do not receive funding, or they require manual checks at regular intervals, which is understandably time-consuming and inefficient.

2.3 Drivers of water level changes:

2.3.1 Rivers

The varying stages of the hydrological cycle are the principal contributors impacting river water levels (Acreman et al., 2013). Heavy rain and snowfall increase the quantity of catchment runoff, which feeds into rivers and therefore increases water flow. However, periods of drought have the opposite effect. Both evaporation of water into the air and infiltration into the riverbed result in a reduction in water level. Human impacts such as water withdrawal, dam construction, and irrigation also cause a change in river depth.

2.3.2 Oceans

The biggest driver of tidal changes is the effect of the gravitational pull that the Moon and the Sun have on Earth (McCully, 2006). The elevation of the tide varies in a semidiurnal timescale, depending on the magnitude of directional pull from the Sun or Moon. When a point on Earth directly faces either the Sun or the Moon, the ocean bulges at this location, causing a high tide. Conversely, when a point is facing away from the Sun or the Moon, the ocean level drops, causing low tide. This system works on a twelve-hour cycle, as the Earth spins around its axis, which creates two high tides and two low tides every day.

The severity of tides also ranges yearly due to the impact of these celestial bodies. The Sun and the Moon rotate in cyclical patterns relative to the Earth and therefore have periods of maximum and minimum effect known as Spring and Neap tides (US Department of Commerce, 2014). A Spring tide occurs when the Sun and Moon are aligned with each other, resulting in a combined gravitational pull, causing a higher tide than usual. A Neap tide has the opposite effect, occurring when the Sun and Moon are perpendicular to one other relative to Earth, and so the gravitational forces cancel each other out. As the Moon orbits the Earth every solar month, both of these events occur around every two weeks.

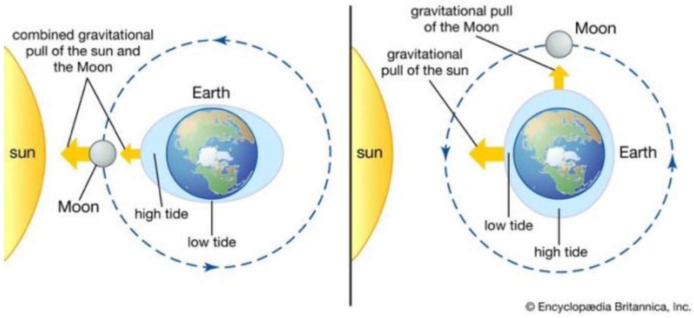

Figure 2 - Tidal effects caused by the Sun and Moon (Britannica, 2011)

Accurate tidal predictions can be made using current models, however, the tides that occur do not always follow this predicted pattern (US Department of Commerce, 2013). This is due to tidal anomalies. Serval factors can cause tidal anomalies or other deviations from the typical tide pattern. The shape of the coastline and other land masses such as sea stacks and arches create friction in the water, which affects the level of both the low and high tides. The climate can also cause tidal anomalies, with strong offshore winds moving ocean water away from coastlines, which can cause exaggerated low tides (US Department of Commerce, 2013). If there is high atmospheric pressure, sea levels are depressed which can also lead to lower tides than expected. The depth of the ocean also affects the tide, as the gravitational pull of the Sun and Moon have a larger impact on shallow water, resulting in more extreme tide changes. One of the benefits of tide gauges is that they collect useful data which can be used to understand the statistics of these tidal anomalies, which in turn allows for a more thorough design of coastal infrastructure and thus more effective prevention of coastal erosion.

2.4 Existing instruments for water level measurements:

Staff gauges are an example of a low-cost water level instrument. They are extremely cheap to produce and relatively simple to set up. These gauges are rulers made of either plastic or wood, which are fixed vertically in the water. Taking measurements requires manual recording of water height relative to the ruler at regular intervals. (US Department of Commerce, 2017). Staff gauges are commonly found in rivers or harbours and are usually accurate to within 1cm or 2cm.

Pressure transducers are instruments often used in rivers, that use hydrostatic pressure to calculate the depth of water (SHOM, 2012). These are devices, which are placed on the riverbed, that use a pressure sensor to convert the hydrostatic pressure into a distance measurement. They are extremely accurate and record the data automatically, however, they can be expensive, so are used sparingly. The sensor is measuring the relative change in depth at the same location, so they are often used in manmade vessels such as large water tanks. However, when used on rivers, they will calculate the change in depth relative to a predefined datum.

Other examples of automatic river gauges used in the UK include radar and ultrasonic gauges. They are fixed above the water level, sending out radar and ultrasonic waves. The time for the waves to reflect off the water is measured and then used to calculate the distance (Kubasky, 2020). More advanced ultrasonic sensors also can determine whether an object is moving or not, and the speed it is travelling, by sending out an array of sound waves (Paulet et al., 2016). Most cheap ultrasonic sensors have a greater error margin at small distances, so they are better suited for measuring distances over 40cm. They are extremely accurate and easy to set up in less accessible locations, as long as there is a permanent structure for the sensor to be mounted onto.

2.5 Citizen science:

Citizen science is a type of scientific research that involves the participation of members of the public in the collection and analysis of data (Haklay et al., 2021). It massively benefits scientific research by allowing data to be collected from any location at a very low cost. However, the only downside is the potential lack of quality control. This method enables individuals to contribute to research projects, aiding the progression of larger scientific studies. These projects can be found online, allowing people to volunteer their assistance in tasks, ranging from collecting data in the field to just reporting observations. This data that is collected by the public, will also be checked and analysed by the professionals within the scientific body or research centre leading the study before it is published.

An example citizen science project that monitors environmental impacts, is the URwatair project, which is organised by the Faculty of Engineering at Aristotle University in Greece (EU Citizen Science, 2021). This initiative provides low-cost rainwater flow meters and air quality sensors to people willing to participate, as seen in Figure 3. These sensors can be set up at people’s homes to collect data, which is then sent back to the University, where a map of results is created. This is a great example of how low-cost equipment, and the scientific intrigue of the general public, can help to collect large amounts of environmental data.

Figure 3 - Low-cost air quality sensor (URwatair, 2019)

The CoastSnap project is another useful example of an environmental citizen science initiative. It was created by the University of New South Wales as a method of analysing the changing coastlines of beaches (Harley et al., 2019). Stainless steel phone mounts (Figure 4) were set up at accessible locations, overlooking beach areas. Members of the public could then place their phones in the case and take a photo of the beach. These images could then be uploaded to CoastSnap's app or posted to social media with a unique identification number for each location. The images can then be processed using software created by the university to plot the change in the shape of the coastline.

Figure 4 - CoastSnap phone cradle (Moran, 2020)

People all over the world are involved in citizen science projects. The largest organiser is a platform called Zooniverse (University of Oxford, n.d.). This was initially created by the University of Oxford, to help classify and sort thousands of images of galaxies, however, its extensive growth means that it is now regarded as the world's leading and most frequently used platform for these projects. There are now over a million people globally that are participating in research hosted on Zooniverse.

One of the aims of this project is for the final solution to act as a citizen science project. The device should be low-cost and easy to set up so that any science or nature fanatic could help to monitor changing river and tide levels.

2.6 Optical methods for environmental monitoring:

There is adequate research on the use of cameras and image processing to monitor different areas within the environment. It is apparent, however, that there are flaws in these techniques, as they are either too complicated or too expensive to be used for a citizen science project.

A team of engineers from the Pukyong National University in Seoul developed a method for observing the change in a coastline using smartphones (Kim et al., 2013). They used the built-in cameras to create a 3D model of the entire beach area using triangulation and known reference measurements. The cameras were calibrated using an accelerometer and a magnetometer to reduce the effects of lens distortion. A comparison was made of the accuracy of the results when using different smartphones, as well as actual cameras. Overall, this proved to be an extremely accurate method for monitoring a changing coastline but is too complicated for simply measuring the change in the water level of a river or harbour.

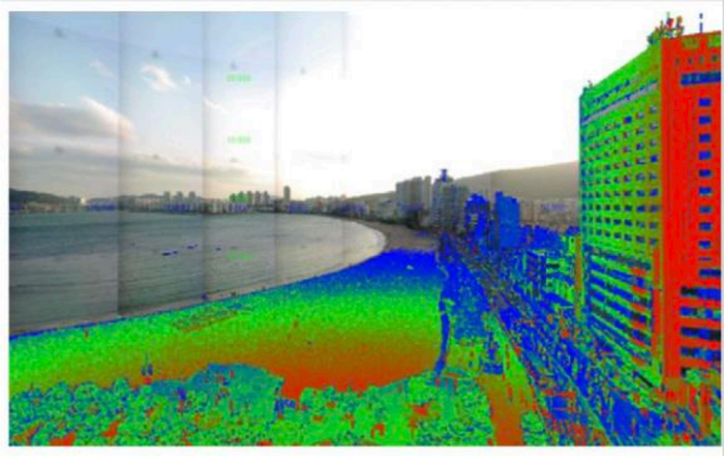

Figure 5 - Model of beach area overlayed on a photo (Kim et al., 2013)

In 2017, researchers at the University of Newcastle in Australia designed an off-grid camera, that calculated how safe a highly visited rocky platform was, based on current tide and wave conditions (Power et al., 2017). It was powered by a solar panel and controlled by a Raspberry Pi, which allowed the data to be collected automatically for approximately 30 days. This method produced an accurate description of the rocky shoreline, and the equipment used in this study could undoubtedly be adapted for use by water level gauges. However, the biggest disadvantage of this paper, is that it aimed to be a low-cost solution, yet the total cost and setup of each camera is over $3000, which is too expensive for the average enthusiast (Power et al., 2017).

The University of São Paulo published a paper in 2015, which used image-processing techniques to measure the depth of urban streams in Brazil (Ortigossa et al., 2015). An existing security camera, pointing at the site, was adapted to take photos at regular intervals. These photos were then passed through image processing software, made up of a variety of filters, and a known reference line, to measure the height of the water. The collected data was then compared to a river gauge at the site, to show the effectiveness of this method. Although this research is an effective example of a camera-operated river gauge, it is not a standalone project, because it relies on an expensive, existing security camera.

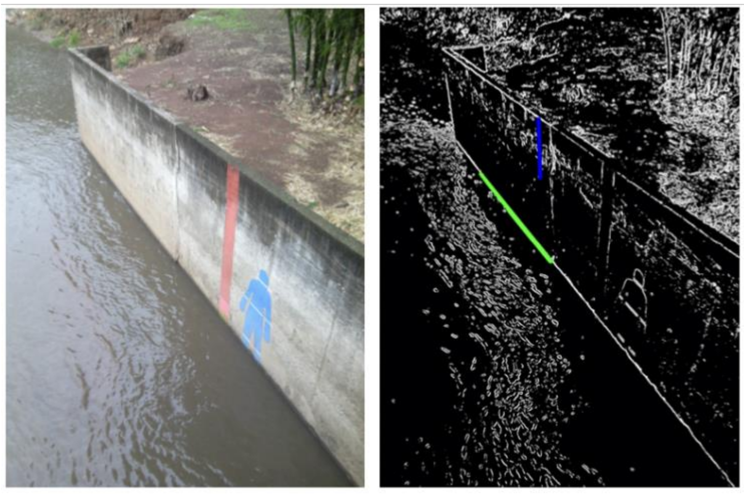

Figure 6 – Output of image processing with reference line (Ortigossa et al., 2015)

2.7 Theory of image processing:

Image processing is extremely important for analysing data collected by cameras and photography. Artificial intelligence (AI) and machine learning techniques are often utilised for image processing tasks, such as object recognition, image classification, and facial recognition (IBM, n.d.). Machine learning involves creating a model, which is trained using large data sets (Brown, 2021). The model is then able to identify trends within the data, and when given new inputs, it can predict values and variables.

Supervised learning is a method of machine learning which trains the model using labelled data (IBM, n.d.). This is where a correct output is provided for each input, and the model can resultantly calculate trends. Examples of this include logistical regression, linear regression, and support vector machines. Unsupervised learning uses unlabelled data, which means no correct output is provided. The aim is to train the model to identify patterns or relationships in the data, rather than to make predictions based on known output labels (IBM, n.d.). This is achieved using clustering techniques such as hierarchical clustering and the k-means algorithm.

Although machine learning can be used to find extremely accurate data from images, it would not be the most effective method for this research. For a model to produce adequate results it requires a large amount of input data to be trained (AI Forum, 2021). For a machine learning model to be effective, it must uphold the industry standard, that a model must be trained with ten times more input data, than the number of model parameters. However, machine learning would not be appropriate for this study. This is because there is insufficient existing data on the water depth, therefore building a model would be difficult. Furthermore, this research does not aim to predict future water levels, instead will involve a live water gauge, seeking to investigate the current water depth.

The alternative for this project is to use image thresholding for edge detection. Thresholding is a technique that converts a greyscale image into a binary image, by converting each pixel into either a 1 or 0, based on how light or dark they are compared to a given threshold (Samopa et al., 2009). This binary image can be used to detect edges because it creates a severe contrast between the background and foreground pixels.

An example algorithm that uses this concept is the Canny edge detection algorithm (Ahmed, 2018). This involves initially reducing the background noise of the image, using a Gaussian blur filter. The Sobel operator, which is built into the Canny edge detection algorithm, then compares each pixel in the image to the surrounding pixels. If there is a significant contrast in brightness between the pixel and its neighbours, then it is considered to be an edge and the pixel is given the value of 1. However, if the contrast is subtle, the pixel is categorised as a 0. This results in a binary image, in which the edges of the original image can be seen. The Canny edge detection algorithm is then able to take this image, along with input values for the required minimum line length and maximum line gap, to detect all the straight lines in the image. The lines that are detected in the image could be used for a variety of means, such as medical screening, fingerprint recognition, and robotic vision.

2.8 Error

In alignment with necessary accuracies for gauges in both the UK and international networks, water level gauges should aim to limit error to less than 1cm (Woodworth and Smith, 2003).

The root mean square error (RMSE) is an effective method to calculate the error of measurement data (Chai and Draxler, 2014). This method has been successfully utilised by the University of Strathclyde to calculate the error of electronic tide gauge records around the world (Pytharouli et al., 2018). RMSE is a statistical metric that evaluates the error within data. For a data set of size *n* values with (i = 1, 2, …, n), the error of each value e_i is found as the difference between the expected value and the measured value. The RMSE can then be calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {e_i}^2} \tag{1}$$

The RMSE value for a water level gauge should therefore aim to be lower than 1cm.

Calculating the relative accuracy of the measurements provides another means of investigating the precision of data (Banas, 2020). The difference in values is used to find the accuracy of a device as a percentage:

$$accuracy = \frac{actual\ value - (actual\ value - measurement)}{actual\ value} \times 100\% \tag{2}$$

Therefore, using this calculation can provide an accuracy percentage of a water level gauge, by comparing the measured values against the true value.

2.9 Literature review conclusion:

It can be seen from the above research that due to tidal anomalies and a changing climate; it is important to monitor the changing levels of tides and rivers as frequently as possible. The current solutions tend to either be too complicated or too expensive to be used for a citizen science project, which is one of the aims of this research. Citizen science projects are extremely effective, as they are both cost-efficient and can collect a large amount of data through very little work from each participant. For image processing to be used in this context, it is clear that machine learning is not the best option for this research, due to the lack of input data and the aim to calculate current water levels. Therefore, image thresholding and edge detection will be used to analyse the images taken by the camera gauge in this study. However, a potential hindrance to using cameras and photos as a method for environmental monitoring is their inability to work at night and when the lighting conditions are poor. This was not identified in the existing research but is an important implication for the design of a water level gauge. This research will therefore also look at the possibility of an ultrasonic sensor as an alternative design for a low-cost water level gauge.

2.10 Context of this study:

To build upon the existing research, an investigation into the possibility of low-cost water level gauges will be completed in the following way:

- Two different water level gauges will be designed, with a focus on them being low-cost and easy to set up and use. This is important if they are to be used as part of a citizen science project.
- Test the use of a camera module connected to a microcontroller to investigate the possibility of an image-processing-oriented water level gauge, as described in the literature review.
- Explore the option of using an ultrasonic sensor as a low-cost water level gauge.
- Compare the accuracy of these gauges to existing pressure transducers using the root mean square error.
- Access how lighting conditions and the time of day affect the accuracy of the results for the two designs.

3. EQUIPMENT

This chapter describes the equipment used to build the water level gauges for this research.

3.1 Image processor

3.1.1 ESP32-CAM

The combination of an ESP32-CAM and ESP32-CAM-MB (Figure 7) creates a microcontroller that can take images. Attached to the module is an OV2640 2MP camera that can take photos with a resolution of 1600 x 1200 pixels. The ESP32-CAM has built-in Wi-Fi, Bluetooth, a real-time clock, and a microSD card reader. The ESP32-CAM-MB makes it possible for code to be uploaded to the microcontroller. For this research, it was designed so that every 15 minutes the ESP32-CAM would wake up from deep sleep, take a photo and save it to the SD card, and then go back to sleep. This allowed for automatic data collection whilst reducing the energy demand of the device.

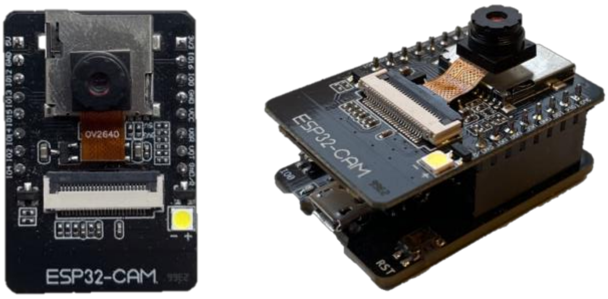

Figure 7 – ESP32-CAM and ESP32-CAM-MB

3.1.2 Power and protection

A 5V power supply containing four AA batteries provided power to the ESP32-CAM-MB (Figure 8). A waterproof Tupperware acted as a protective case for all the components. A drill was used to create a hole in the base of the case for the camera lens to sit flush, and to prevent the images from being distorted by the plastic. Foam padding inside the case prevented the camera from moving.

Figure 8 – Protective case for ESP32-CAM

3.2 Ultrasonic sensor

3.2.1 Arduino Nano

An Arduino Nano (Figure 9) was used as the microcontroller of this design. This is a compact and low-cost microcontroller board based on the ATmega328P. The Nano has digital and analogue pins, and a USB port and can be connected to other modules to improve its capabilities. It can be programmed using the Arduino Integrated Development Environment (IDE) and is commonly used for electronics projects, robotics, and automation.

Figure 9 – Arduino Nano (CPC, n.d.)

3.2.2 Ultrasonic sensor

A JSN-SR04T waterproof ultrasonic sensor (Figure 10) was used to measure the distance between the gauge and the water level. The sensor is compatible with Arduino boards and transmits an ultrasonic wave with a frequency of 40kHz. It has a range of 0.25m – 5m and an accuracy of 0.5cm. The sensor emits an ultrasonic wave which then reflects off the water surface, and then the sensor detects the reflected wave. The time taken is measured and then the distance can be calculated using the speed of sound (340 m/s).

Figure 10 - JSN-SR04T Ultrasonic sensor (Amazon, n.d.)

3.2.3 Additional modules

Two further modules were used to build this gauge. A real-time clock (Figure 11a), and a microSD card reader (Figure 11b). The real-time clock allowed for a time value to be associated with the collected data, which was important for measuring the change in water level over time. The microSD card reader was used to save the measured distances and corresponding time to a microSD card.

a) b)

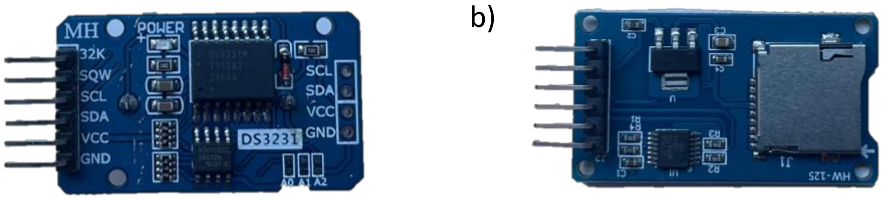

Figure 11 – a) DS3232 real-time clock b) microSD card reader

3.2.4 Power

A 5V battery pack with four AA batteries was used to power the Arduino and the other components. This provided enough power for the gauge to run for an entire day and collect data automatically.

3.2.5 Wiring

The battery pack and additional modules were connected to the Arduino Nano using an electronic breadboard and DuPont wires, with the configuration shown in Figure 12.

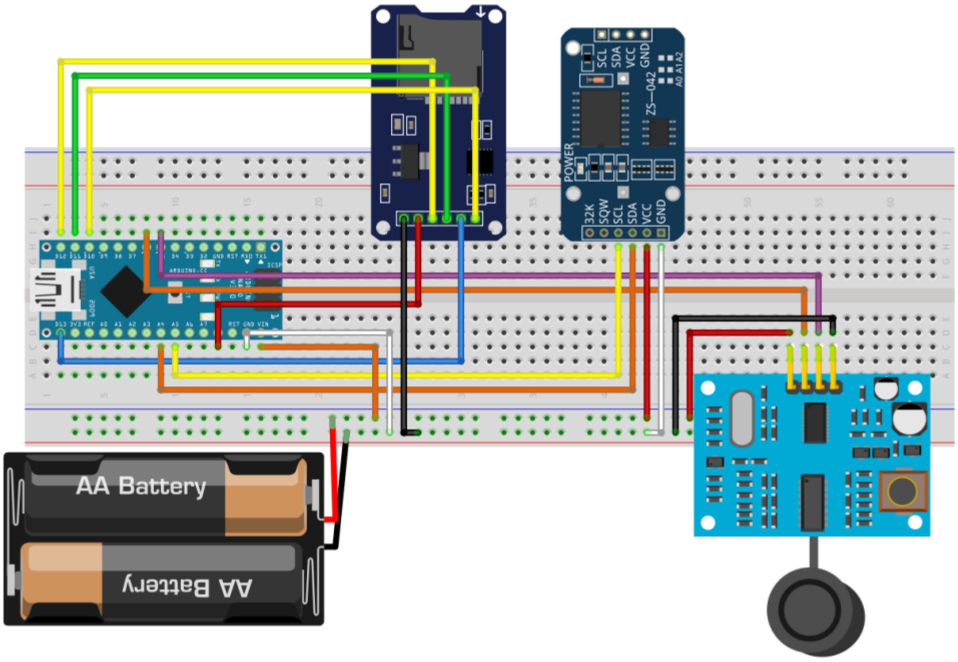

Figure 12 – Wiring configuration of the ultrasonic sensor

3.2.6 Protection

All the components were combined and stored in a waterproof Tupperware, with a hole drilled in the base for the ultrasonic sensor to sit flush with the base of the case.

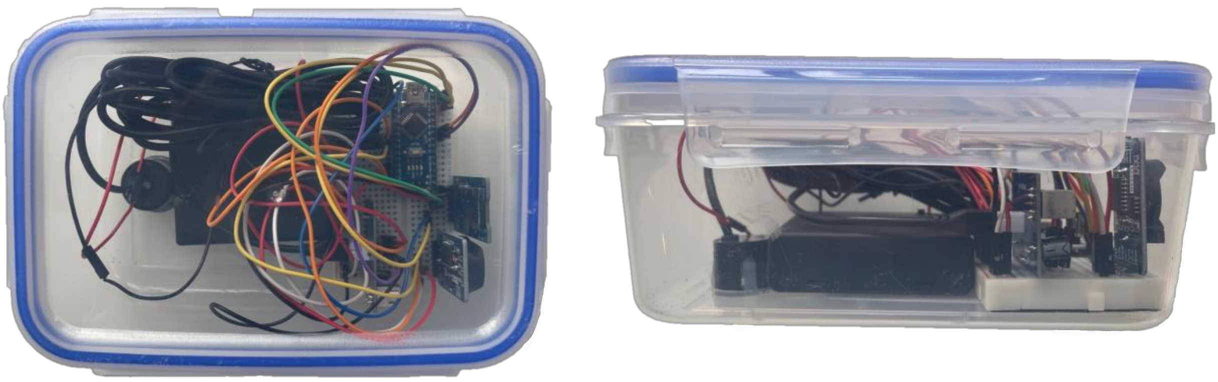

Figure 13 – Protective case for the ultrasonic sensor

4. METHODOLOGY

This chapter describes the methods used during the testing process of these designs.

4.1 Site selection

The gauges needed to be compared to actual data from existing water level gauges. The ‘Check for Flooding’ service and Environmental Agency provided by the UK government shows the location of every water level gauge in Great Britain (Met Office, n.d. and Environmental Agency, n.d.). The current depth and measurements from the previous five days are displayed in the form of a graph and can also be exported as a CSV file. Three sites were used for this research, one for the ESP32-CAM, and two for the ultrasonic sensor, as this was tested on both a river and at a harbour. The sites were selected based on their ease of access, location, and suitability for each gauge.

4.1.1 ESP32-CAM - river site

For the image processing software to work effectively, the water must be contained by a vertical and relatively smooth wall, it also benefits from having an existing staff gauge at the site, so that the measured values can be validated. The existing river gauge on Brislington Brook (Figure 14) was used as the chosen site to test the ESP32-CAM. It is located under a bridge that has concrete retaining walls as part of the foundations.

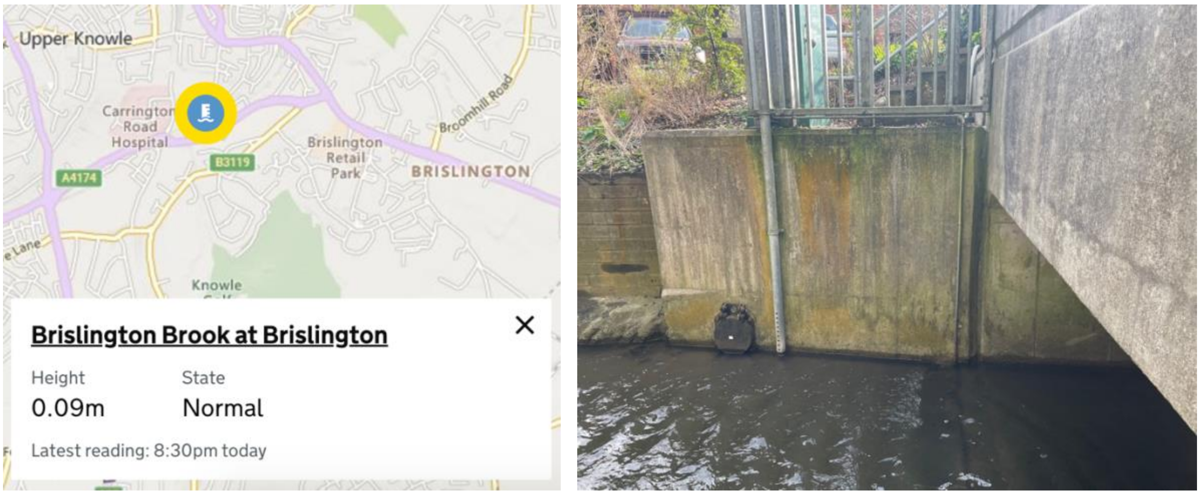

Figure 14 – Location of Brislington Brook (left; Met Office, n.d.) and the existing river gauge (right).

4.1.2 Ultrasonic sensor - river site

The ultrasonic sensor only had the requirement of needing a suitable structure to attach it to, since it needed to be directly above the water, whilst also being perfectly horizontal. The river gauge at the Bath Destructor Bridge (Figure 15) was used for this research. The side walls of the river were used to support the sensor.

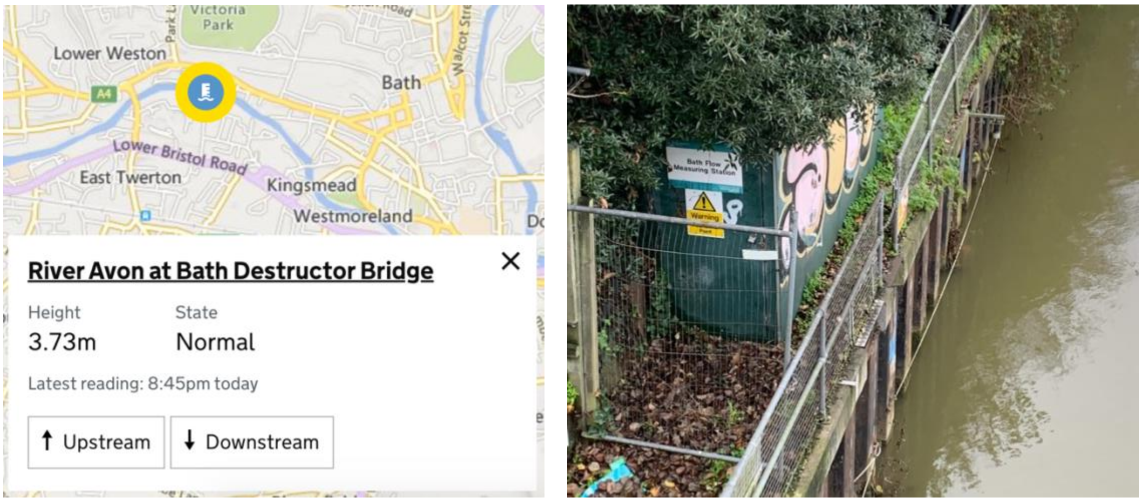

Figure 15 - Location of Bath Destructor Bridge (left; Met Office, n.d.) and the existing river gauge (right).

4.1.3 Ultrasonic sensor - tidal site

To test the ultrasonic sensor at a tidal location, Leith Docks in Edinburgh was used (Figure 16). The water level varies by roughly 4m between high and low tides, which is measured by an existing pressure transducer. This site also has concrete walls for the sensor to be attached to.

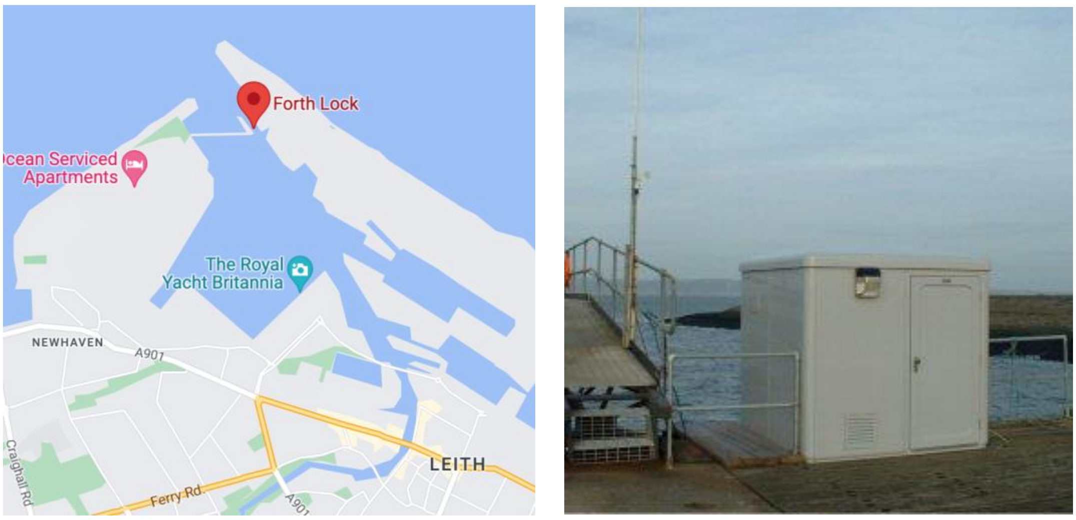

Figure 16 - Location of Leith Docks (left; Google, 2023) and the existing tidal gauge (right, National Oceanography Centre, n.d.).

4.2 Data collection

4.2.1 ESP32-CAM

The ESP32-CAM was programmed to take a photo every 15 minutes and save it to the microSD card. These images were then transferred from the microSD card to a laptop to be run through the image processing software. The protective case containing the ESP32-CAM was secured to a metal railing using duct tape as seen in

Figure 17. It was angled so that the waterline, the top of the concrete wall, and the existing staff gauge were all in the frame. The staff gauge was used as a reference distance in the image processing. The camera was then left for an entire day to capture the change in water level, after which, the batteries powering the device required changing as they only lasted 25 hours. This process was repeated over three days.

Figure 17 – ESP32-CAM set up on site

4.2.2 Ultrasonic sensor

The ultrasonic sensor was programmed so that every 5 minutes it would turn on, measure the distance to the water and save the data with the corresponding time to a text file on the microSD card. This text file was then transferred to a laptop, and the data could be extracted. The sensor was placed inside a protective case as described previously and secured to a wooden plank using duct tape. The sensor was left to record data for 24 hours at a time since the batteries needed to be changed every day. This process was repeated for 6 days at the Bath Destructor Bridge and for a single day at the Leith Docks. In Bath, a rope was attached to the plank using a hoop screw, which was then tied to the metal fence as an extra safety measure. At the Docks, there was no fence for the rope to be attached to, so a steel plate was used to act as a counterweight to secure the sensor.

Figure 18 – Ultrasonic sensor set up in Bath (left) and Leith (right).

4.3 Data processing

4.3.1 ESP32-CAM

The images collected by the ESP32-CAM were inputted into an image processing software that was written for this research. The source code can be found at: https://github.com/joebadger24/Waterlevel-ImageProcessing. It was designed using the OpenCV library and written in Python. Firstly, the contrast of the image is slightly increased to emphasize a greater difference between the lighter and darker pixels.

Figure 19 – Original image (left) and increased contrast (right).

The image is then converted to grayscale to further emphasize the contrast in pixels. To remove any background noise from the image, a low-pass filter known as a Gaussian Blur is used to remove any high-frequency pixels. This allows for the edge detection filters to work more effectively.

Figure 20 – Grayscale of image (left) and Gaussian Blur applied (right).

The Canny edge detection filter is then applied, which is a multi-layer algorithm that compares the intensity of each pixel to the pixels surrounding it. Upper and lower bound thresholds were given to optimise the output based on the brightness of the image. This results in a binary image where pixels that are deemed to be an edge are white, and the rest of the pixels are black. This binary image is then passed through a Hough transformation, which applies math principles to detect straight lines. It takes all the white pixels as points on a graph and can create equations of straight lines, which are then plotted on the original image. The transformation has inputs for minimum line length and maximum line gap, which means the relevance of lines can be filtered.

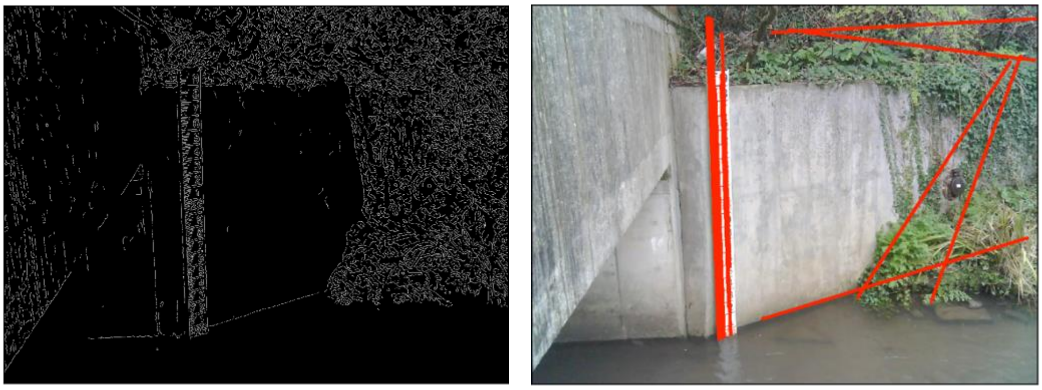

Figure 21 – Binary image produced by Canny edge detection (left) and Hough transformation (right).

The lines from the Hough transformation were filtered so that they had to be parallel with the ruler. A constant line was drawn on all the images, that was adjacent to the top of the ruler (the blue line in Figure 22). The point of intersection between this constant line and the furthest left line from the Hough transformation was calculated. This resulted in a new line being drawn that represented the length of the ruler that is visible in the image, as indicated by the red line in Figure 22. The length of this line in pixels was found and then converted to meters by reading the respective value from the ruler in the first image. This process was then repeated for all the images to obtain the change in height over the testing period.

Figure 22 – Final output of image processing.

4.3.2 Ultrasonic sensor

The data from the sensor was inputted into an Excel file to be compared to the real results. The change in distance to the water from the sensor was multiplied by a negative one so that it represented the change in water height.

5. RESULTS

This section shows the results measured from the testing of the gauges.

5.1 ESP32-CAM

Figure 23 presents the change in water level in centimetres against time, with a comparison against the data from the Check for Flooding service provided by the UK government and the Met Office.

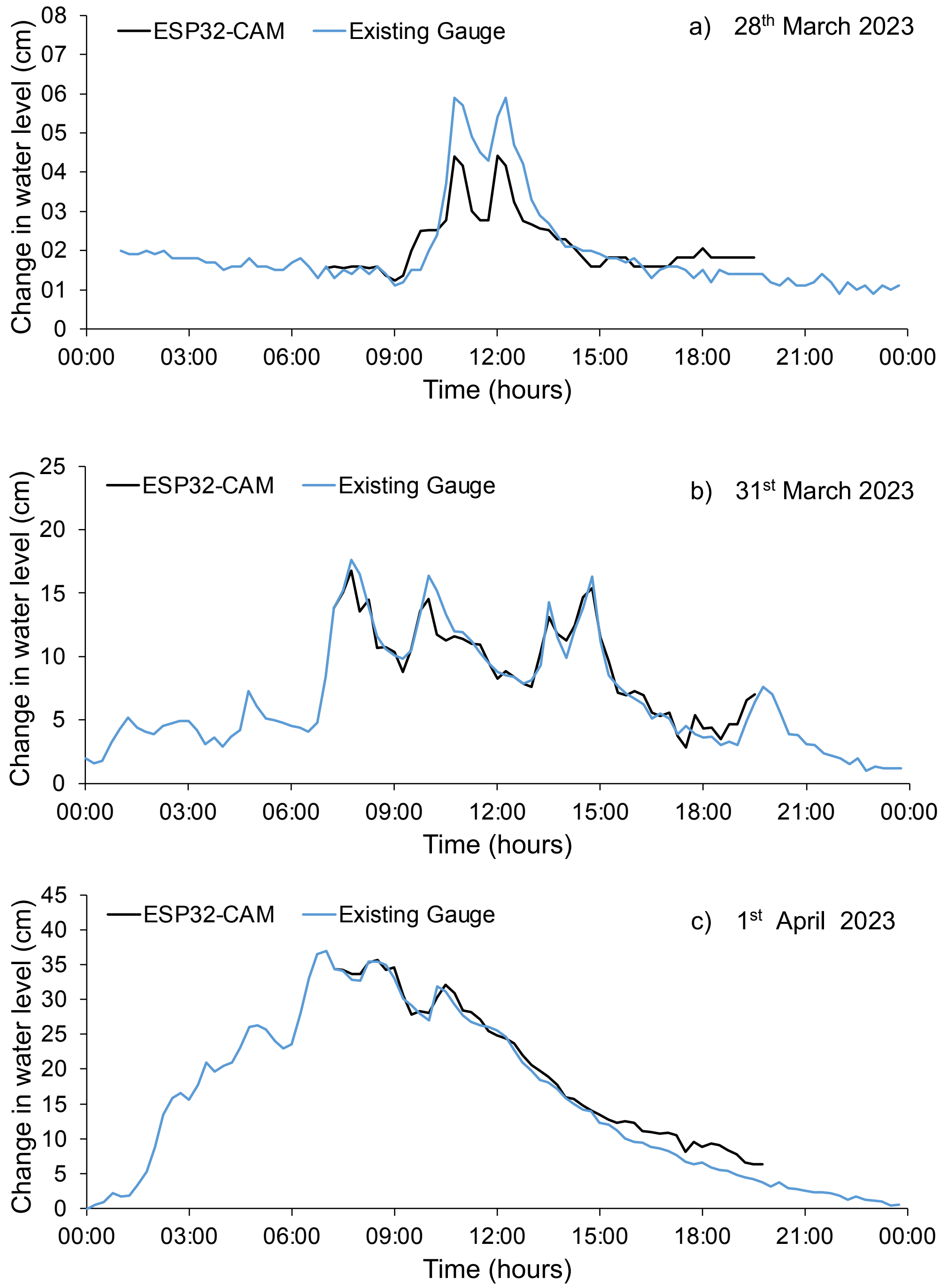

Figure 23 – Change in water level against time measured using the ESP32-CAM.

5.2 Ultrasonic sensor

5.2.1 River data

The following graphs show the change in water level over the six testing periods carried out at Bath Destructor Bridge. The data is compared to the measurements obtained from the Check for Flooding service provided by the government and the Met Office.

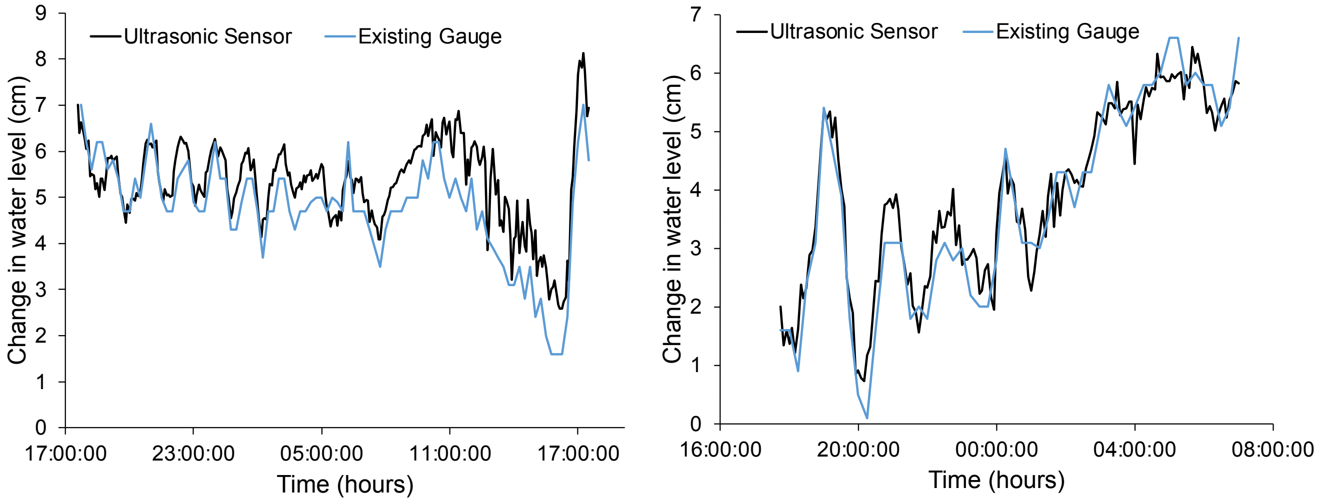

Figure 24 – Results from 17:30 28th March 2023 to 17:30 29th March 2023 (left) and 17:40 29th March 2023 to 07:00 30th March 2023 (right).

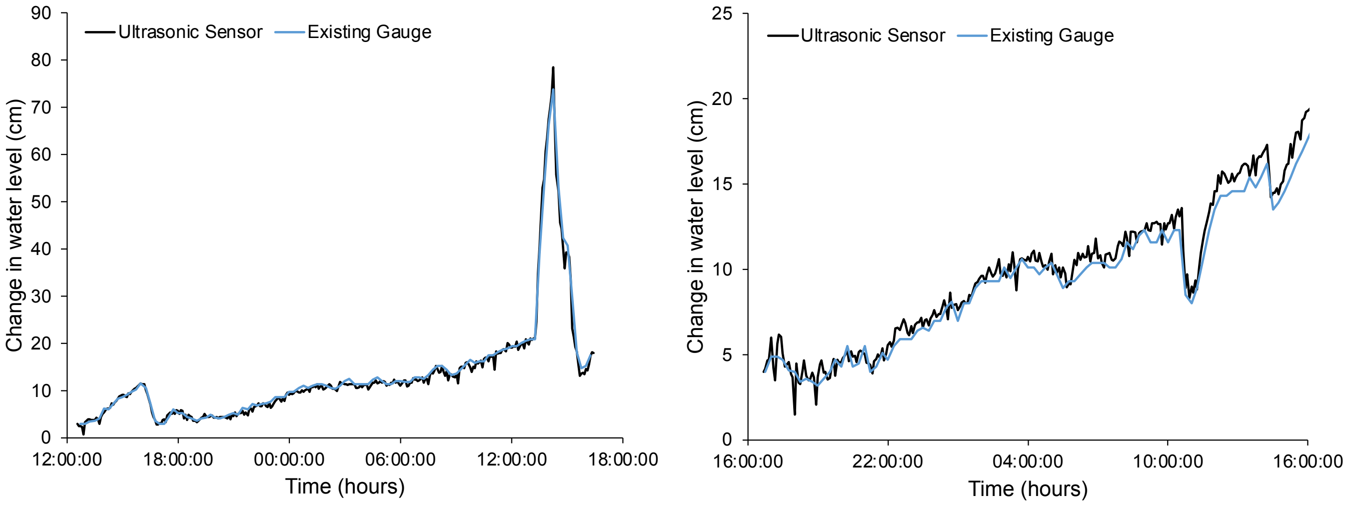

Figure 25 – Results from 12:30 30th March 2023 to 16:30 31st March 2023 (left) and 16:30 31st March 2023 to 16:30 1st April 2023 (right).

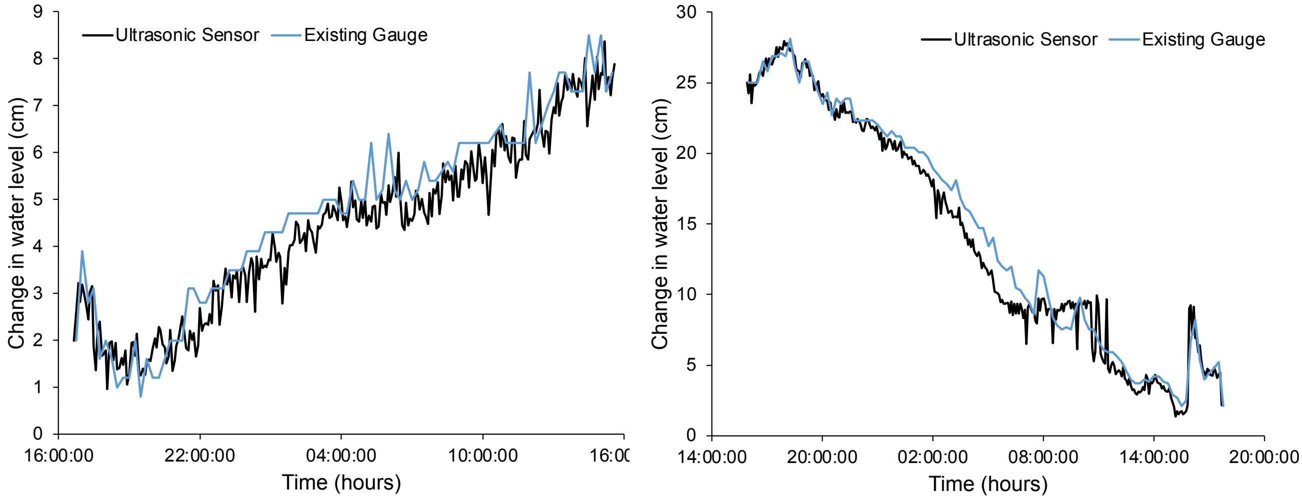

Figure 26 – Results from 16:40 1st April 2023 to 15:40 2nd April 2023 (left) and 15:55 2nd April 2023 to 17:40 3rd April 2023 (right).

5.2.2 Tidal data

Figure 27 presents the results from the testing of the ultrasonic sensor at the Leith Docks. It shows the relative change in water level over 24 hours. The data is compared to measurements provided by the UK government's Environmental Agency.

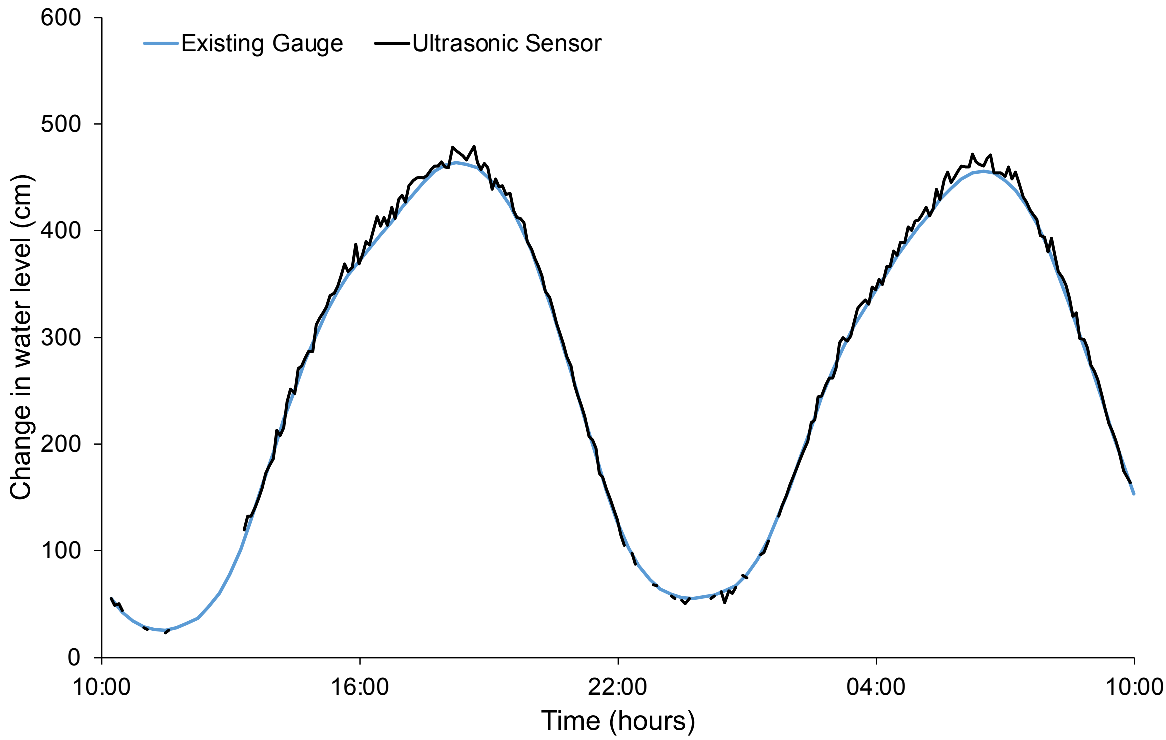

Figure 27 – Ultrasonic tidal results from 10:00 10th April 2023 to 10:00 11th April 2023.

5.3 Comparison of gauges

The data from the testing was analysed to find the root mean square error (RMSE) and the relative accuracy of both gauges, as described in section 2.8.

Table 1 - RMSE values for both gauges over the testing period.

Gauge	Testing Period	Sum Error^2	n	(Sum E^2)/n	RMSE (cm)
ESP32-CAM	1	27.37	51	0.54	0.73
ESP32-CAM	2	56.26	50	1.13	1.06
ESP32-CAM	3	144.67	51	2.84	1.68
Average ESP32-CAM					**1.16**
Ultrasonic - River	1	190.49	288	0.66	0.81
Ultrasonic - River	2	50.18	160	0.31	0.56
Ultrasonic - River	3	668.81	335	2.00	1.41
Ultrasonic - River	4	206.92	285	0.73	0.85
Ultrasonic - River	5	116.50	276	0.42	0.65
Ultrasonic - River	6	541.33	310	1.75	1.32
Average Ultrasonic - River					**0.93**
Ultrasonic - Tidal	1	2915.60	73	39.94	6.32
Average Ultrasonic - Tidal					**6.32**

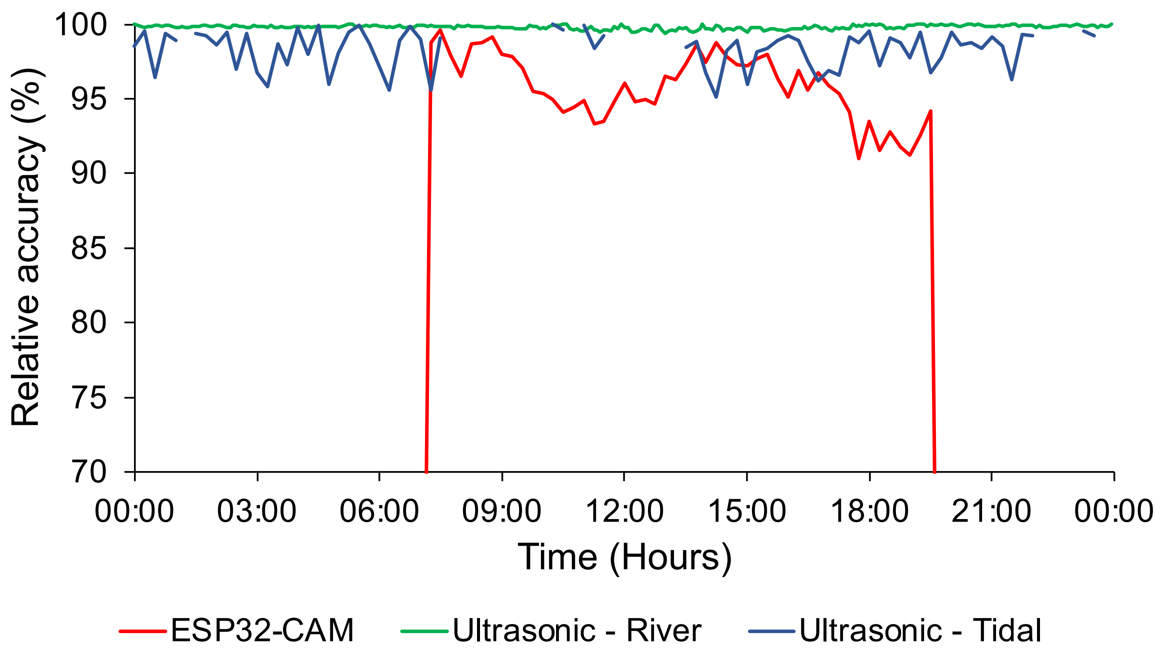

Figure 28 - Relative accuracy of both gauges as a function of time.

6. DISCUSSION

6.1 ESP32-CAM

The data collected highlighted that the ESP32-CAM worked effectively as a river gauge, with an average RMSE value of 1.16cm across the testing period. This is relatively close to the targeted value of <1cm, which was defined in the literature review. The data from Tuesday 28th of March appears to be the most inaccurate on the graph, however, this is due to the smaller scale of the y-axis. The data from this day recorded the lowest error value of 0.73cm. This is because the water level only varied by roughly 4cm all day, due to a lack of rainfall. In contrast, the data from Saturday 1st of April appears to be extremely accurate on the graph, due to the larger scale on the y-axis which is reducing the visibility of the error. On this day, the gauge recorded an error value of 1.68cm, which is significantly higher than the average error. There was a large amount of rainfall, and the water level increased by 35cm over the day before returning to the initial level. Therefore, it can be assumed that there is a positive correlation between the volatility of the water level change and the extent of error in measurements produced by the ESP32-CAM.

Figure 28 shows the relative accuracy of the device as a function of time. It is clear from this graph that in both the mid-morning and late afternoon there is a drop off in accuracy. This is due to lighting conditions because if there is too much or too little sunlight, then the contrast between the water and the retaining wall is less obvious. Therefore, the ability of the image processing software to distinguish the boundaries between pixels is reduced. Inevitably, this impacts the accuracy of the results, as the true position of the waterline is skewed.

The greatest drawback of the ESP32-CAM is the fact that it only works during daylight hours. This has the potential to cause serious issues if heavy rainfall or storm surges are not detected during the night. At the time of testing, the first useful images were taken at 7:00 am and 7:15 am, and the final images were all taken at 19:45 pm. This aligns exactly with the time of sunrise and sunset on the respective days. Figure 6.1 shows the annual change in sunrise and sunset times in Bath. The light blue area shows the amount of daylight on each day. In the summer months, this gauge would be more effective, as there are days with over 16 hours of daylight. However, during the winter, there are days with as little as 8 hours of sunlight. This will impact the amount of reliable data that can be collected per day.

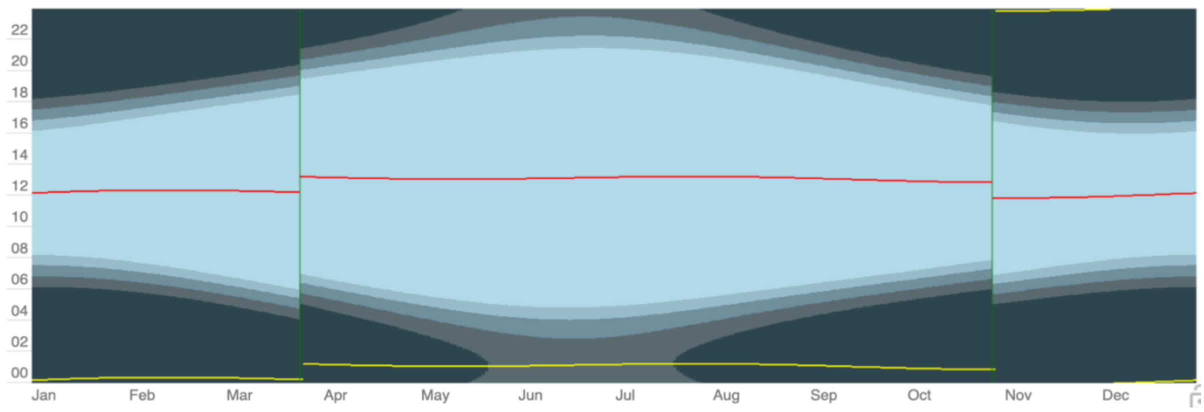

Figure 29 – 2023 Sun graph for Bath (Timeanddate, 2023).

The duration of daylight at a specific site is also dependent on the global latitude of the area. Therefore, sites which are located closer to the equator, are likely to work better for data collection with this gauge, due to the more consistent daylight.

A further issue with the ESP32-CAM as a water level gauge is the restrictions it faces with site selection, to ensure that the image processing can work. The necessity for a vertical retaining wall means that many remote and natural rivers with no surrounding infrastructure could not be monitored using this technique. Throughout this research, it was found that the presence of a vertical staff gauge also helped with the effectiveness of the image-processing software. This restricts the number of possible sites even further. Initially, the software was designed so that it would detect the waterline and the top of the concrete retaining wall, then find the distance between these lines. However, when the water level dropped, areas of the wall would remain wet and thus the colour of the concrete remained dark. The software would often detect this as the waterline, which would give overestimations of the water depth. This can be seen in Figure 30.

Figure 30 – An older version of image processing output.

6.2 Ultrasonic sensor

The data from the ultrasonic sensor suggests that it would work very successfully as a river gauge. The results from the testing on the river in Bath produced an average RMSE of 0.93cm, which is less than the targeted value of 1cm. The third and sixth periods of testing produced the largest error, 1.41cm, and 1.32cm respectively, and were also the periods with the biggest fluctuation in water level. The second and fifth periods of testing were the most accurate with RMSE values of 0.56cm and 0.65cm respectively. These periods had relatively small changes to the water level. Therefore, the assumption can be made that there is also a positive correlation between the fluctuation in water level changes and the accuracy of the results produced by the ultrasonic sensor on rivers.

Results from the testing at Leith Docks showed that the ultrasonic sensor has the potential to also work as a tide gauge. The calculated RMSE value for this period of testing was 6.32cm. This is much greater than the target value of 1cm, however, this target value does not account for the additional error caused by wave height. The water level was measured every 5 minutes, and there was no way of knowing at which point the reading was on the undulating wave. Inevitably the water height varies whether it is measured nearer the peak or trough of the wave. Therefore, there is a risk that the reading is not representative of the actual water level, thus causing an additional error. This finding is reinforced by the data collected from the river, which suggests that the larger the variation in water level, the greater the error, and since the tide causes a 4m variation, a larger error value is expected.

An additional problem with the ultrasonic sensor as a tide gauge is the maximum range of the device. The JSN-SR04T ultrasonic sensor that was used in this research has a maximum range of 5m. Measuring any distance greater than this risks the potential of the device to give false readings. This can be seen with the missing data from the tidal testing as shown in Figure 31.

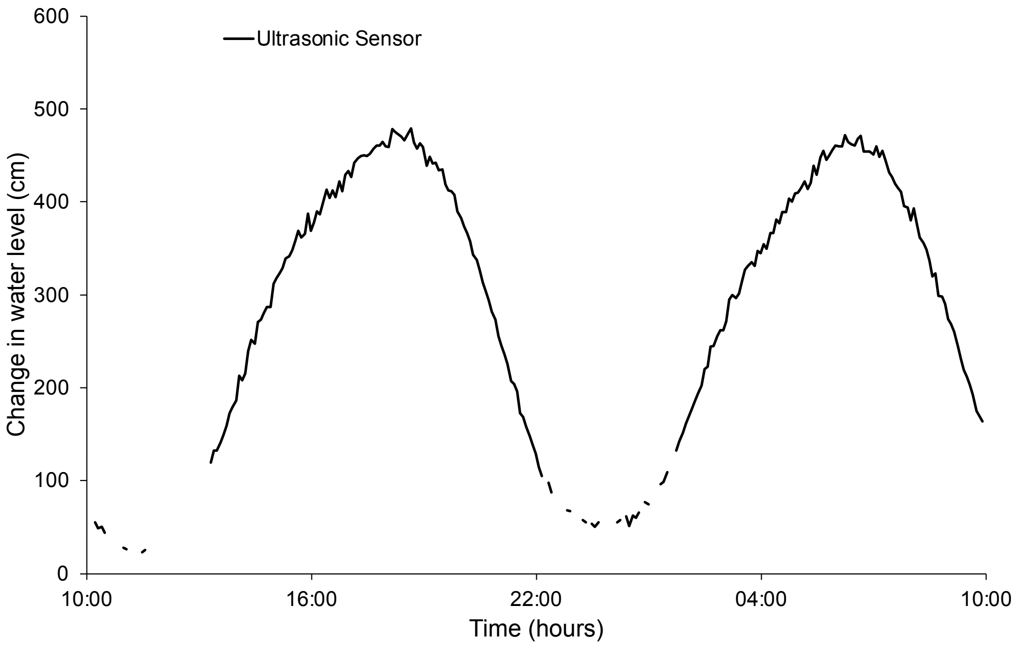

Figure 31 – Ultrasonic tidal results without existing gauge data

This occurred because the sensor was positioned on the harbour wall, which was fixed more than 1m above the level of high tide. As the tide dropped by 4m, the water level dropped to more than 5m below the ultrasonic sensor, resulting in false readings which have been excluded from the data. This could cause a problem for many harbours and ports that have similar tide variations and infrastructure. However, investing in a more expensive ultrasonic sensor with a greater range would provide a simple solution to this issue.

6.3 Comparison of gauges

The data has highlighted that both the ESP32-CAM and ultrasonic sensor are suitable alternatives for standard water level gauges. The ultrasonic sensor slightly outperformed the ESP32-CAM with regards to RMSE value when they were both tested on a river. To gain a better understanding of how they perform against each other, further testing should be conducted where both gauges are set up at the same site and left to record data over the same period of time.

An approximate cost of each gauge has been calculated, and the results are displayed in Table 2. The ESP32-CAM was cheaper to build, with a total cost of £22.95, compared to the ultrasonic sensor which cost £39.70. It must also be highlighted that for the ultrasonic sensor to work more effectively as a tide gauge, a more expensive sensor should be used, which would increase the total price.

Table 2 – Approximate cost comparison of all components used for each gauge. Additional materials for site installation are not included.

ESP32-CAM		Ultrasonic Sensor	
Component	**Cost (GBP£)**	**Component**	**Cost (GBP£)**
ESP32-CAM + ESP32-CAM-MB	£ 10.99	Arduino Nano	£ 6.15
MicroSD Card	£ 4.97	JSN-SR04T Ultrasonic Sensor	£ 10.74
Battery Pack	£ 2.49	DS3231 Real Time Clock	£ 3.95
4 x AA Batteries	£ 3.50	MicroSD Card Module	£ 2.95
Protective Case	£ 1.00	MicroSD Card	£ 4.97
		Battery Pack	£ 2.99
		DuPont Wires	£ 1.65
		Breadboard	£ 3.30
		Protective Case	£ 3.00
Total	**£22.95**	**Total**	**£39.70**

It should be noted that the prices given in the Table 2 are for purchasing individual components. The total price of each gauge would be reduced if they were being produced on a larger scale.

The design of the ESP32-CAM is easier to build and set up than the ultrasonic sensor. It has fewer components, and once the necessary code has been uploaded to the device, it only requires power to be connected through the micro-USB port. The ultrasonic sensor, however, has many different parts and requires some basic understanding of microcontrollers to put it together. Nonetheless, with sufficient instructions and diagrams, both gauges would still be a suitable level of difficulty to be used as part of a ‘build at home’ citizen science project.

Both devices require a flat surface to be installed at a site, however, the ESP32-CAM could be set up using a tripod. The ultrasonic sensor needs to sit directly above the water, so it either needs to be cantilevered from a structure, like it was in this research or be mounted underneath a bridge. These are both suitable options and can be altered to work with the environment of the site.

7. CONCLUSIONS

The conclusion of this research is that both the ESP32-CAM and ultrasonic gauges that were designed for this study could be used as alternative low-cost water level gauges.

This study found that the ESP32-CAM had an average RMSE value of 1.16cm when tested at Brislington Brook. Although it produces relatively accurate results, it can only collect data during daylight hours, which varies from 8 to 16 hours of the day throughout the year. This device is also very restricted with site selection, which means there are a limited number of locations where it could be used effectively. Furthermore, the image processing software that is used alongside the ESP32-CAM is also site-specific and requires altering based on the site environment and the positioning of the camera. Although this design works as a water level gauge, it is less suitable to be used as part of a citizen science project, due to its restrictions and difficulty of set up.

The data showed the ultrasonic sensor had an average RMSE value of 0.93cm when tested on the river at the Bath Destructor Bridge, and 6.32cm at Leith Docks. The device produces results with the same accuracy throughout the day and does not require any specific lighting conditions. Although it is the slightly more expensive of the two designs, it would still be an appropriate piece of equipment to be used for citizen science research. The only limiting factor is the range of the ultrasonic sensor if the device is being used for tidal monitoring. However, as mentioned earlier, the use of a more expensive ultrasonic sensor with a greater range would be introduced in the design.

8. FUTURE RESEARCH

8.1 Data collection

Collecting data over additional days would lead to a more precise value for the average error of both gauges. The ESP32-CAM was only tested over three days, and the ultrasonic sensor was only trialled for a single day using tidal data. This was due to limitations of timing and travel abilities. The next step of this research would be to set up both gauges at multiple different locations and collect water level data for numerous weeks. A further area of potential exploration would be to install two of the ESP32-CAMs at a site in slightly different positions. The data from them both could be compared, to see if the results vary when the camera is situated differently.

It would also be beneficial to create a website, which shows the live data as it is collected from the gauges. For this to be possible, the devices would need to be connected to the internet. This could be achieved with portable hotspots or with existing internet on-site. Instead of uploading the data to the microSD cards, the devices could instead upload the data to an online database. The processing of the data would take place in the backend of the website and the results could be displayed live. For the gauges to work for an extended period of time, they would need to be powered by solar energy rather than batteries. This would allow for entirely off-grid data collection and would eliminate the need for someone to replace the batteries every day.

8.2 ESP32-CAM

If the image quality of the device is increased, then the image processing software will work more effectively, due to the higher number of pixels which are being analysed. To accomplish this, a more expensive camera module could be used, such as the OV5640. It works with the ESP32 and increases the image quality to 2592x1944 pixels, as opposed to the 1600x1200 pixels provided by the OV2640 in this research.

Exploring the possibility of using infrared night vision cameras could eliminate the restriction of the ESP32-CAM only working during the day. These cameras work with Raspberry Pi microcontrollers and use infrared LEDs to capture images in the dark. If the images produced by this method worked with the image processing software, then this could significantly improve the suitability of this design.

If enough images are collected, with their corresponding water depth marked on the image, then there is a possibility that machine learning could be used as an alternative to the image processing software. The model could be trained to identify the waterline, and then calculate the difference between that line and a constant line drawn on the image. This would be a more effective solution, as the software would not need to be updated for different sites. However, it could not be proven to work until enough data is collected.

8.3 Ultrasonic sensor

As mentioned earlier in this paper, one of the improvements that could be made to the ultrasonic gauge is to use a more expensive ultrasonic sensor. The URM37 is an alternative option that has a range of 8m and is only very slightly more expensive than the JSN-SR04T used in this research.

An additional feature that should be added to this gauge is a digital spirit level. This would improve the accuracy of the results, as the ultrasonic sensor needs to be perfectly flat so that it is directly above the water. The addition of a digital spirit level would mean that the alignment of the device could be checked when it is being installed on-site. An MPU-6050 is a combined accelerometer and gyroscope which can be used with an Arduino to act as a spirit level. They are relatively cheap and could easily be incorporated into the current design.

8. REFERENCES

Acreman, M. and Holden, J., 2013. How wetlands affect floods. *Wetlands*, *33*(5), pp.773-786.

Ahmed, A.S., 2018. *Comparative study among Sobel, Prewitt and Canny edge detection operators used in image processing.* Baghdad: University of Baghdad.

AI Forum, 2021. *How much training data is needed for machine learning?* [Online]. AI Forum. Available from: https://ai-forum.com/opinion/how-much-training-data-is-needed-for-machine-learning/#:~:text=Regression%20analysis%3A%20To%20train%20a,the%20number%20of%20model%20parameters [Accessed 29 December 2022].

Amazon, no date. *Waterproof ultrasonic sensor module, 5V ultrasonic wave distance measuring board ranging module ultrasonic ranging module with water-resistant sensor* [Online]. Amazon.co.uk: Business, Industry & Science. Available from: https://www.amazon.co.uk/Waterproof-Ultrasonic-Distance-Measuring-Water-resistant/dp/B08BLQQCVQ/ref=sr_1_4_sspa?crid=3GYSOMCY69XHQ&keywords=ultrasonic%2Bsensor&qid=1681040063&sprefix=%2Caps%2C383&sr=8-4-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1&smid=AMFXAS6GKYXYK [Accessed 16 April 2023].

Banas, T., 2020. *How to calculate relative accuracy* [Online]. Sciencing. Available from: https://sciencing.com/calculate-relative-accuracy-6069718.html [Accessed 16 April 2023].

BBC, 2022. *River Severn flooding: Homes and businesses evacuated*, *BBC News* [Online]. BBC. Available from: https://www.bbc.co.uk/news/uk-england-shropshire-60475077 [Accessed 18 April 2023].

Brown, S., 2021. *Machine Learning, explained*, *MIT Sloan* [Online]. MIT. Available from: https://mitsloan.mit.edu/ideas-made-to-matter/machine-learning-explained [Accessed 30 December 2022].

Chai, T. and Draxler, R.R., 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature*. Geoscientific model development*, *7*(3), pp.1247-1250.

CPC*,* no date. *Arduino nano 3.0 board - A000005* [Online]. CPC. Available from: https://cpc.farnell.com/arduino/a000005/board-arduino-nano/dp/SC09659 [Accessed 16 April 2023].

Environmental Agency, no date. *Tide Gauge Readings*, *Defra Data Services Platform* [Online]. Environmental Agency. Available from: https://environment.data.gov.uk/flood-monitoring/tidegauge/index.html#filter=7&station=E70839 [Accessed 16 April 2023].

EU Citizen Science, 2021. *URwatair* [Online]. EU Citizen Science. Available from: https://eu-citizen.science/project/40 [Accessed 29 December 2022].

Google, 2023. *Leith Docks* [Online]. Available from: http://maps.google.co.uk [Accessed 13 April 2023].

Haklay, M.M., Dörler, D., Heigl, F., Manzoni, M., Hecker, S. and Vohland, K., 2021. *What is citizen science? The challenges of definition*. Switzerland: Springer.

Harley, M.D., Kinsela, M.A., Sánchez-García, E. and Vos, K., 2019. Shoreline change mapping using crowd-sourced smartphone images. *Coastal Engineering*, 150, pp.175-189.

Hogarth, P., Pugh, D.T., Hughes, C.W. and Williams, S.D.P., 2021. Changes in mean sea level around Great Britain over the past 200 years. *Progress in Oceanography*, 192, p.102521.

IBM, no date. *What is Computer Vision?* [Online]. IBM. Available from: https://www.ibm.com/uk-en/topics/computer-vision#:~:text=Machine%20learning%20uses%20algorithmic%20models,tell%20one%20image%20from%20another. [Accessed 30 December 2022].

IBM, no date. *What is supervised learning?* [Online]. IBM. Available from: https://www.ibm.com/uk-en/topics/supervised-learning [Accessed 30 December 2022].

Kim, J., Lee, S., Ahn, H., Seo, D., Seo, D., Lee, J. and Choi, C., 2013. Accuracy evaluation of a smartphone-based technology for coastal monitoring. *Measurement,* 46(1), pp.233-248.

Kubasky, K., 2020. *OTT radar water level monitoring in Rivers* [Online]. NexSens. Available from: https://www.nexsens.com/blog/ott-radar-water-level-monitoring-in-rivers.htm [Accessed 31 December 2022].

McCully, J.G., 2006. *Beyond the moon: A conversational common sense guide to understanding the tides*. Singapore: World Scientific.

Met Office, no date. *Bath - find river, sea, groundwater and rainfall levels* [Online]. GOV.UK. Available from: https://check-for-flooding.service.gov.uk/river-and-sea-levels?q=Bath [Accessed 16 April 2023].

Moran, B., 2020. *Fighting Beach erosion, one smartphone picture at a time*, *WBUR News* [Online]. WBUR. Available from: https://www.wbur.org/news/2020/11/20/coastsnap-beach-erosion-sandwich-cape-cod [Accessed 9 February 2023].

National Oceanography Centre, no date. *Leith Tide Gauge Site*, *Leith tide gauge site | National Tidal and Sea Level Facility* [Online]. National Oceanography Centre. Available from: https://ntslf.org/tgi/portinfo?port=Leith [Accessed 16 April 2023].

Paulet, M.V., Salceanu, A. and Neacsu, O.M., 2016. *Ultrasonic radar*. Romania: IEEE.

Pytharouli, S., Chaikalis, S., & Stiros, S. C., 2018. Uncertainty and bias in electronic tide-gauge records: Evidence from collocated sensors. *Measurement*, *125*, pp.496-508.

OpenCV, no date. *Canny edge detection* [Online]. OpenCV. Available from: https://docs.opencv.org/4.x/da/d22/tutorial_py_canny.html [Accessed 29 December 2022].

Ortigossa, E.S., Dias, F., Ueyama, J. and Nonato, L.G., 2015. *Using digital image processing to estimate the depth of urban streams*. São Paulo: University of São Paulo.

Power, H.E., Kinsela, M.A., Stringari, C.E., Kendall, M.J., Morris, B.D. and Hanslow, D.J., 2017. *Automated sensing of wave inundation across a rocky shore platform using a low-cost camera system*. Sydney: University of Newcastle.

Samopa, F. and Asano, A., 2009. *Hybrid image thresholding method using edge detection.* Hiroshima: Hiroshima University.

SHOM, 2012. *Pressure Tide Gauges* [Online]. REFMAR. Available from: http://refmar.shom.fr/en/documentation/instrumentation/les-maregraphes-a-capteur-de-pression;jsessionid=2A4F76C713EB722281BD38CBA31DAF09#:~:text=Placed%20on%20the%20seabed%2C%20they,density%20to%20determine%20water%20depths. [Accessed 30 December 2022].

Timeanddate, 2023. *Bath, England, United Kingdom - Sunrise, sunset, and daylength, April 2023*, *Sunrise and sunset times in Bath* [Online]. timeanddate. Available from: https://www.timeanddate.com/sun/uk/bath [Accessed 16 April 2023].

University of Oxford, no date. *To the Zooniverse and beyond* [Online]. University of Oxford Research. Available from: https://www.ox.ac.uk/research/research-impact/zooniverse-and-beyond [Accessed 29 December 2022].

US Department of Commerce, 2017. *What is a tide gauge?* [Online]. NOAA's National Ocean Service. Available from: https://oceanservice.noaa.gov/facts/tide-gauge.html [Accessed 30 December 2022].

URwatair, 2019. *News* [Online]. URwatair. Available from: http://www.urwatair.gr/urwatair_news.html [Accessed 29 December 2022].

US Department of Commerce, 2013. *What affects tides in addition to the Sun and Moon? - tides and water levels* [Online]. NOAA's National Ocean Service Education. Available from: https://oceanservice.noaa.gov/education/tutorial_tides/tides08_othereffects.html [Accessed 29 December 2022].

US Department of Commerce, 2014. *Why do we have spring tides in the fall?* [Online]. NOAA's National Ocean Service. Available from: https://oceanservice.noaa.gov/facts/springtide.html [Accessed 29 December 2022].

Woodworth, P.L. and Smith, D.E., 2003. A one year comparison of radar and bubbler tide gauges at Liverpool. *The International hydrographic review*, 4(3), pp.42-49.

World Bank, 2022. *Water Resources Management* [Online]. World Bank. Available from: https://www.worldbank.org/en/topic/waterresourcesmanagement#2 [Accessed 31 December 2022].