UNSW Water Research Laboratory

UNSW SYDNEY

Sydney WATER

Sydney Water Aquatic Monitoring Program

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Nearshore marine intertidal pilot study
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Sydney WATER

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1. Introduction

1.1. Background

Sydney Water operates an extensive wastewater network that spans the Greater Sydney, Blue Mountains and Illawarra area. Included within this system are several nearshore ocean outfalls which discharge effluent treated to various standards into the ocean. Sydney Water is required by the NSW Environment Protection Authority (EPA) under Environment Protection Licences (EPLs) to monitor the impact of these discharges on the environment (Sydney Water, 2023). While the EPLs allow for some impacts within the mixing zone of outfalls, there are potential impacts to the ecology outside of these mixing zones that need to be monitored. Monitoring the nearshore receiving environment is challenging due to access and safety issues associated with wave action, submerged rocks and the exposed nature of intertidal rock platforms.

Sydney Water's receiving water licence compliance monitoring is outlined in the Sydney Water Aquatic Monitoring (SWAM) program. The SWAM program was established in 2023, after its predecessor, the Sewage Treatment System Impact Monitoring Program (STSIMP), was reviewed in 2021-2022 (van Dam et al, 2023). Under the SWAM program (and previously the STSIMP), only one of Sydney Water's nearshore Water Resource Recovery Facilities (WRRF) (Shellharbour WRRF) and two control sites are monitored due to access and safety concerns at the other nearshore locations. The monitoring involves physically accessing the intertidal rock platforms to take photographs of random 0.25 m^2 quadrats for later analysis. The results from the 2024-25 intertidal survey at Shellharbour using this traditional method are presented in Volume 1 Section 4.4.7.

Following the review of the STSIMP and development of the SWAM program, a number of recommendations were made by an independent expert review panel to trial new methods (herein referred to as Pilot Studies) to monitor the nearshore outfalls:

- Rec 12-3 That an asymmetrical design that includes a potentially impacted site (outfall) assessed against multiple control (reference) sites sampled over time is used for detecting potential ecological impacts from Sydney Water activities.
- Rec 12-4 That drone technology be adopted for outfall and associated reference sites where this is feasible, i.e. intertidal rock platform present - Shellharbour, Warriewood and Bombo.
- Rec 12-6 That appropriate reference sites be identified for comparisons with outfall sites for drone monitoring.
- Rec 12-8 That the existing sampling frequency of every year is retained, and sampling continue in late winter/spring.
- Rec 12-9 That water quality be sampled in surface water for comparison with intertidal communities and in bottom waters for comparison with subtidal communities
- Rec 12-10 That the stressor (analytes) and biodiversity parameters listed in the SWAM program are adopted for monitoring water quality and macroalgae/macroinvertebrates.

- Rec 12-12 That additional intertidal reference sites be identified for Shellharbour, Warriewood and Bombo.
- Rec 12-13 That the suitability of drone technology for sampling the intertidal ecology at Shellharbour and new reference sites be investigated.

To assist with addressing these recommendations, Sydney Water engaged the UNSW Water Research Laboratory (WRL) to expand on an existing macroalgae survey methodology developed by WRL in 2017 (Drummond and Howe, 2018). The 2017 method used unmanned aerial vehicles, (drones), to measure potential impacts to the ecological community on intertidal rock platforms adjacent to three nearshore ocean outfalls. Components developed by WRL for the 2024-25 pilot study and report, can be found as a standalone technical report (Tucker et al., 2025).

The 2024-25 pilot study expanded the use of drone technology to reduce the need for personnel to physically access rock platforms when undertaking impact assessments. As per the recommendations in van Dam et al (2023), it also included macroinvertebrates and water quality. The methodologies developed for this study included:

- expand on Drummond and Howe (2018) to survey macroalgae coverage using drones
- develop a novel method for using drones to survey macroinvertebrates
- trial the suitability of a water quality sampling drone to collect samples in turbulent offshore water

To test these methodologies, they were applied at three nearshore ocean outfalls (Figure 1-1) which discharge secondary treated water to the nearshore environment at depths between 3 and 8 m, namely:

- Warriewood
- Shellharbour
- Bombo

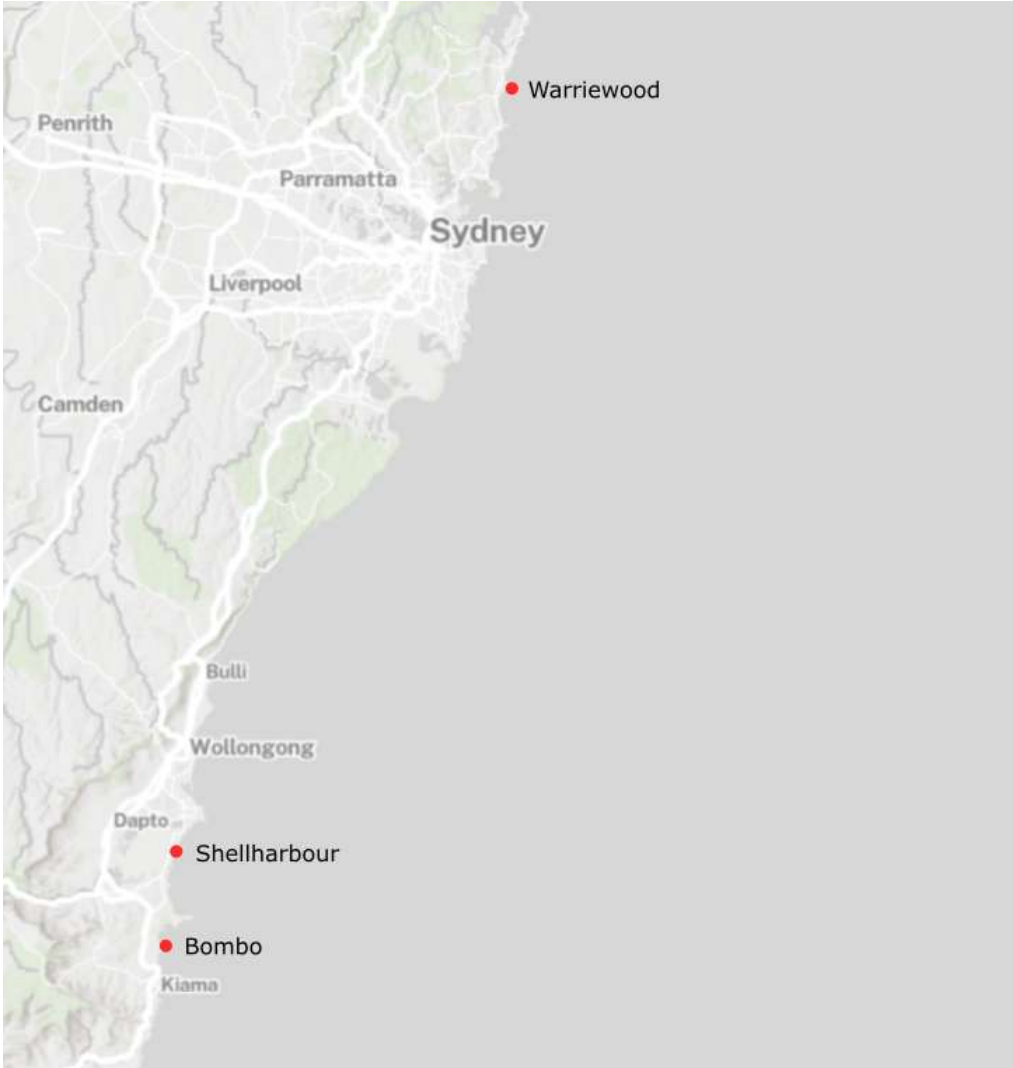


Figure 1-1 Discharge locations (source: ESRI)

1.2. Aims and objectives

The aim of the pilot study was to develop suitable methods to survey the ecological health of intertidal rock platforms adjacent to nearshore outfall discharges using drones, and to collect water samples adjacent to the rock platforms using a water sampling drone.

Pending the success of the 2024-25 pilot study, the results would form part of ongoing annual monitoring to support Sydney Water in meeting its obligations under its EPLs. Monitoring was therefore completed as a collaboration between UNSW and Sydney Water staff, with the objective of ensuring knowledge transfer to Sydney Water for future monitoring efforts.

The overarching aims and objectives of the intertidal monitoring program, as per the SWAM (2023) program, are presented in Table 1-1.

Table 1-1 Recommended aims and objectives for the nearshore marine water quality and ecosystem health sub-program (rock platform sampling)

Proposed aim	Revised proposed objectives
(i) Assess the direct impacts of Sydney Water's shoreline WRRF ocean discharges on (a) water quality and (b) ecosystem health (intertidal macro algae and invertebrates).	*Stressors:* a. To compare physico-chemical water quality, including nutrients, for each WRRF outfall and reference site with relevant water quality objectives (where available), for the current year. b. To investigate the joint relationship between all physico-chemical water quality parameters, including nutrients, to identify the most meaningful parameters impacting water quality for each WRRF outfall and reference site, and comparing the current year with the relevant historical record. c. To compare outfall with reference site physico-chemical water quality, including nutrients, for each site grouping (i.e. for each WRRF) for the current year and over the relevant historical record.
	Ecosystem receptors: d. To compare outfall and reference site ecological responses, (macroalgal % covers and macroinvertebrate counts) for each site grouping (i.e. for each WRRF) for the current year and over the relevant historical record. e. To assess spatial and temporal trends in the ecological dataset for each WRRF outfall and reference site grouping over the relevant historical record. f. Where significant differences in macroalgal % covers/macroinvertebrate counts or multivariate community analysis between outfall and reference sites are detected for the current year, further investigate the potential drivers (e.g. by comparing with water quality data).

2. Review of existing monitoring methodology

2.1. Overview

The following section provides a review of existing techniques and technologies that can be utilised for the detection of macroalgae on rock platforms. For context, Section 2.2 reviews the previous intertidal rock platform investigation methodology completed by WRL (Drummond and Howe, 2018). A review of existing drone technology is then provided followed by an assessment of its suitability for ecological surveys (Section 2.3). Finally, opportunities for further improvements of the existing methodology have been identified and discussed in Section 2.4.

2.2. Review of Drummond and Howe (2018)

Drummond and Howe (2018) completed drone surveys of three ocean outfalls using a multiband Parrot Sequoia camera mounted on a DJI Phantom 3 quadcopter. The Sequoia camera is designed for analysing plant health and captures visible and near infrared wavelength bands (Figure 2-2).

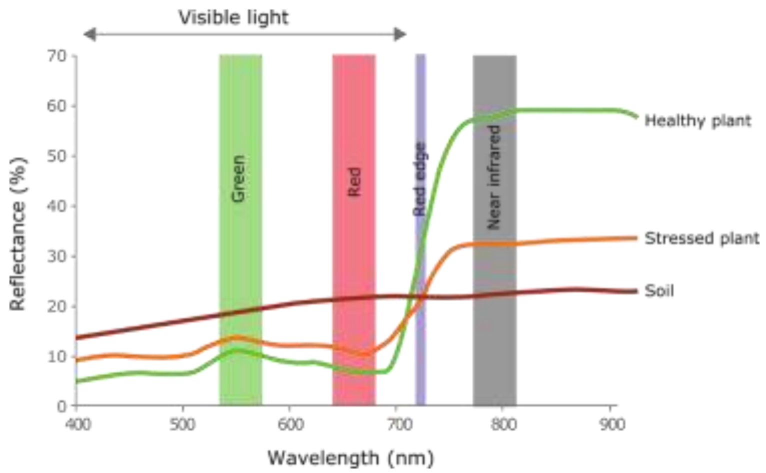


Figure 2-2 Green vegetation reflectance (after Parrot, 2017)

Normalised difference vegetation index (NDVI) images were created from the red (R) and near infrared (NIR) bands, using this formula (Cracknell, 1997):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

The NDVI is a dimensionless number between -1 and +1, with higher values corresponding to healthy dense vegetation (Figure 2-3). A threshold value can then be determined by visual side-by-side comparison of NDVI imagery with RGB imagery (i.e. images use a Red Green Blue colour model) to determine vegetation extent. Note, vegetation can also be classified using RGB thresholding techniques, but the classification process is more complicated, more time consuming, and more difficult to replicate, because three different channels must be considered (red, green, and blue) instead of just one. Subsequently, the NDVI was used to calculate the percent coverage of macroalgae for rock platforms using a zonal statistics calculator in Python.

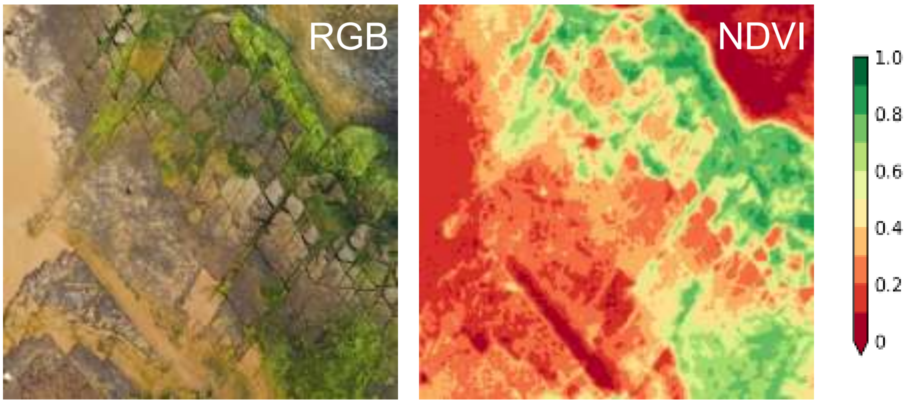


Figure 2-3 Comparison of RGB and NDVI images collected at Warriewood

2.3. Drone selection for ecological surveys

2.3.1. Review of drone use for macroinvertebrate surveys

Drones are increasingly employed for surveying wildlife and vegetation to aid conservation and management efforts. They offer significant advantages over ground surveys, especially when observing large groups of animals and vegetation across large areas (Francis et al., 2020; Ezat et al., 2018; Espriella and Lecours, 2023; Francis et al., 2024).

Prior to the development of drone technology, other methods were used to complete ecological surveys. Examples of these methods include imagery taken from kites (Bryson et al., 2012) and LiDAR/aerial imagery surveys (0.3 m/0.1 m resolution, respectively) (Thorner et al., 2013). Using a 14 megapixel camera at a height of 15 m above ground, Bryson et al. (2012) achieved a 4 mm pixel resolution for their surveys. While these methods focused on classifying habitats, the potential for expansion of the methodology to identify fauna was highlighted during their development.

In many instances, drones have been used to identify or classify habitat (e.g. Duffy et al., 2018; Tait et al., 2019; Monteiro et al., 2021; Ventura et al., 2023; Valdazo et al., 2024), however, this is often limited to habitat type and does not identify individual macroinvertebrates due to resolution limitations. Due to the resolution limitations of drone technology (Murfitt et al., 2017), there has been limited research into using drones for surveying macroinvertebrates. Nevertheless, some existing studies demonstrate the potential of drone technologies. For example, Ha et al. (2024) used a DJI Matrice 300 drone flown at approximately 6 m to capture still images of burrow openings for three crab species. By measuring the burrow sizes, they were able to relate burrow dimensions to organism size and weight based on ground surveys. Similarly, Chand and Bollard (2021) measured benthic macrofauna activity in seagrass habitats by using burrow openings as an index of activity. Burrow counts were made through analysing georectified orthomosaic images collected from a DJI Phantom 4 drone with a MicaSense RedEdge-M sensor flown at a height of 50 m.

Brunier et al. (2022) surveyed intertidal rock platforms comparing RGB and multispectral imagery (0.05 m and 0.025 m resolution, respectively). In their approach, Brunier et al. (2022) found that fauna could be identified using spectral indices developed from the multispectral data. It was noted that their approach was only successful for some species (e.g. in their study oysters could not be identified) and visual inspection of RGB imagery was still required in some circumstances.

Bouet et al. (2024) surveyed macroalgae and gastropods in north-east France using LiDAR and multispectral (MicaSense Altum-PT) sensors mounted to a drone (0.10 m and 0.13 m pixel resolution, respectively). They found that the multispectral sensor performed the best, however, improved results were achieved by combining the data from both surveys. Mapping of gastropods was performed statistically and verified against Citizen Science data using a linear regression. Results only showed a weak correlation of 0.45, indicating limitations in the method.

Schnurawa et al. (2024) completed similar surveys to identify mussel beds in Germany. They used a range of sensors including a Sony QX1 20 mm RGB camera (0.014 m pixel resolution) and a MicaSense Altum multispectral sensor (0.04 m pixel resolution) flown from a WingtraOne drone at heights between 68 and 80 m above the ground. Their surveys were validated against ground-based GPS data of mussel bed areas. As with other surveys, Schnurawa et al. (2024) found that the multispectral data performed best for identifying fauna. In their investigations they also analysed machine learning techniques which were found to improve the accuracy of the analysis. Note, their approach did not seek to identify individual mussels. Duffy et al. (2018) used a similar approach to measure the abundance of mussels on intertidal rock platforms of Portugal. In their analysis, drone image resolution was 0.008 m. Subsequently, they developed a model which incorporated other environmental variables (e.g. wind and wave data) and quadrat surveys to assess the size and abundance of the mussels (i.e. this was not directly calculated from drone data). An analysis by Barbosa et al. (2022) also assessed the abundance of mussels, this time in France. They used a DJI Phantom 4 Pro drone with its inbuilt 8-megapixel camera to achieve a resolution of 0.005 m when flown at a 30 m height. While the extent of mussel population was mapped well (>90%), no attempt was made to detect individual mussels. Barbosa et al. (2022) highlighted that they were fortunate as there was limited algal coverage which could have limited their analysis.

Espriella and Lecours (2023) conducted large scale drone surveys to identify oyster reefs. They utilised a Quantum Trinity F90+ drone with a MicaSense RedEdge-MX Camera (~0.05 m pixel resolution). Their approach focussed on mapping oyster reefs and not individual oysters meaning they did not encounter resolution issues. Similar studies mapping reef units have also been successful but do not identify individual oysters (e.g. Windle et al., 2019). While this is the case, Espriella and Lecours (2023) did highlight the following limitations associated with using drones for ecological surveys:

- Pilots are still required to be at the flight location
- Appropriate launch site selection can be difficult
- Lighting can be an issue limiting flights to solar noon (which is further impacted by tides)
- Wind speed and direction can affect flights

Konar and Iken (2018) completed a survey of algae and macroinvertebrates in Alaska using an Aeryon Scout drone with a 12-megapixel GoPro Hero 3 RGB camera mounted to it. While the exact resolution of imagery was not specified, they commented that the resolution of their imagery was generally sufficient for identifying macroinvertebrates. Konar and Iken (2018) highlighted the following limitations of drone monitoring:

- Identification of species is dependent on the observer and their experience
- Algae cannot be moved out of the way to identify macroinvertebrates (as would be done during ground surveys)
- Camera limitations can cause images to blur (associated with shutter speed)
- While often organisms can be identified to a certain taxonomic level, the exact level is still limited by sensor resolution

Bushnell et al. (2025) recently reviewed the use of drone-based imagery and LiDAR for assessing rocky intertidal habitats. LiDAR data was collected using PandarXT-32 32-Channel Mid-Range LiDAR (0.05 m pixel resolution). Colour imagery was collected using a Zenmuse P1 RGB camera (0.004 m pixel resolution). A DJI Matrice 300 was used for the surveys and flown at a height of 34 m. Bushnell et al. (2025) successfully demonstrated that LiDAR and RGB imagery could be used to visually detect macroinvertebrates (RGB outperformed lidar), however, this was found to be species specific, with only 10 of the 44 known species being identified. A limitation was found in observing smaller species where there was not enough image resolution. Another review of the technology completed by Tait et al. (2021) found further limitations when using drones for ecological surveys:

- Seasonality of species abundance can make repeat surveys difficult
- Accuracy is significantly reduced if there is overlying water (e.g. in rock pools)
- It is difficult to obtain a pixel resolution less than 0.05 m for large areas as flight time is often limited by drone batteries and tides
- Classification of specific algae and macroinvertebrate taxa is often not possible
- Many organisms are not visible directly from above (as they are underneath a rock shelf or algae)

Despite these limitations, Tait et al. (2021) did highlight the overall usefulness of drones for broader habitat extent mapping.

2.3.2. Drone selection criteria

Drone selection criteria for ecological surveys can be categorised into (1) functional requirements and (2) ease of use criteria. Drone functional requirements relate to the drone hardware and include:

- Camera type (e.g. RGB versus multispectral)
- Camera quality (i.e. resolution)
- Other drone sensors (e.g. GPS and proximity sensors)
- Storage capacity

The following drone criteria, which generally relate to the environment where flights are being conducted, should be considered when assessing ease of use:

- Drone flight time
- Drone weight and transportability
- Required take-off and landing space
- Drone capability (e.g. maximum wind speed for flight, options for attachments)

Note, provided these criteria are met, additional considerations may also include the level of training required to operate the drone, usability of flight software, and the cost of the drone.

Selecting the right drone for ecological coastal surveys is crucial due to the challenging flying conditions. Access to coastal platforms often involves navigating difficult terrain on foot, making it essential for the drone to be portable, lightweight, and capable of sufficient flight time to cover the required mapping area. Additionally, precise take-off and landing capabilities are crucial, as space for these operations is typically very limited. Drone size and ease of use are also significant factors, as smaller (<2 kg), more user-friendly drones generally require fewer approvals from the Civil Aviation and Safety Authority (CASA) and are better suited for operation in shared airspace.

Key requirements for drones to conduct macroalgal coverage and macroinvertebrate surveys have been identified in Table 2-2. These criteria were determined based on previous investigations completed by WRL (Drummond and Howe, 2018), based on the review of literature, and through trials completed for this investigation.

Table 2-2 Drone selection criteria

Criteria type	Criteria	Macroalgal coverage survey	Macroinvertebrate survey
Functional	Camera type	Multispectral	RGB
	Camera quality	5 MP	20 MP (minimum)
	Sensor requirements	RTK-GPS positioning	Downward collision sensor
	Storage capacity (based on camera quality)	>20 GB per flight	>1 GB per flight
Ease of use	Flight time	~1 hour, or easy to change battery option	<15 minutes
	Software requirements	Automated transects	N/A
	Drone weight and transportability	Ideally <10 kg total weight	
	Wind resistance capability	Ideally > 6 m/s	
	Required take-off and landing space	Vertical take-off (i.e. quadcopter or Vertical Take Off and Landing (VTOL) capability)	

2.3.3. Available drone technology

A comparison of available drone technology is provided in Table 2-3. Drones equipped with multispectral sensors include the Phantom, Mavic, and Matrice series multirotor helicopters from DJI, and fixed-wing aircraft from eBee. A range of drones with RGB sensors were also compared from DJI and Autel. All drones assessed had a suitable storage capacity (either internal or via an external SD card), suitable flight time, and suitable wind resistance capabilities. Multispectral drones assessed all had appropriate automation requirements. Note, the Phantom 4 DJI drone has been released since the surveys conducted by Drummond and Howe (2018) and subsequently the Phantom 3 model was not considered here.

Note, drone technology outlined in Table 2-3 was assessed as of early 2025. It is anticipated that drone technology will continue to develop and the options presented in this table will become outdated with time.

Table 2-3 Review of drone technology

Drone*	Camera	Camera type	Type	Positives	Negatives	Price
DJI Mavic 2 Pro	Parrot Sequoia+ 16MP	RGB and Multispectral	Quadcopter	Small, light and transportable. Easy to use.	Can no longer be purchased. Requires customised camera.	~$4,000
DJI Mavic 3 Pro[2]	In-built up to 48 MP (effective)	RGB	Quadcopter	Small, light and transportable. Excellent RGB camera (effective 20MP camera, 7x optical zoom).	No multispectral sensor.	~$3,000
DJI Air 3S[2]	In-built 50MP (wide angle), or 48 MP	RGB	Quadcopter	Small, light and transportable. Excellent RGB camera (effective 20MP camera, 7x optical zoom).	Wide angle camera may distort images, no multispectral sensor.	~$1,700
DJI Mini 4 Pro[2]	In-built up to 48MP	RGB	Quadcopter	Small, light and transportable. Lightweight drone with less flight restrictions.	Shorter flight time (still 30 mins), poorer quality camera, no multispectral sensor.	~$1,200
Autel Evo II Pro[2]	In-built 20 MP	RGB	Quadcopter	Small, light and transportable.	Less well-known brand with limited track record.	~$4,000
Autel Evo Nano[2]	In-built 48 MP	RGB	Quadcopter	Small, light and transportable. Lightweight drone with less flight restrictions.	Less well-known brand with limited track record.	~$1,100
DJI Phantom 4 Multispectral	In-built 2 MP	RGB and Multispectral	Quadcopter	Small, light and transportable. Stable in flight.	Can no longer be purchased.	~$6,000
DJI Mavic 3M[1]	In-built 20M MP RGB, 5MP Multispectral	RGB and Multispectral	Quadcopter	Small, light and transportable. Good battery life. Multispectral and RGB imagery synced. Long flight time ~35 minutes. RTK GPS positioning.	Moderately expensive.	~$8000

Drone*	Camera	Camera type	Type	Positives	Negatives	Price
DJI Matrice 350[1]	DJI Zenmuse X3 12.4 MP	RGB and Multispectral	Quadcopter	High quality additional sensors. Multi-payload capacity. Newer models are waterproof. RTK GPS positioning.	Expensive. Large, heavy. Short flight time with payload. Requires larger landing area and additional pilot training.	Drone: ~$12,000 Sensors: $1,000+
SenseFly eBee X	Parrot Sequoia+ 16MP or Duet M 20MP	RGB and Multispectral	Fixed wing	Long flight time (~90 minutes). Can cover large areas. Lightweight. Safer than other drones (reduced risk to others). RTK GPS positioning.	Very expensive. Handles worse in wind. Requires larger landing area and additional pilot training.	~$30,000
DJI Mavic 4 Pro[2]	In-built up to 100 MP (effective)	RGB	Quadcopter	Small, light and transportable. Excellent RGB camera (best available).	No multispectral sensor.	~$3,000

*Review was completed in January 2025 focusing on major manufacturers and latest models.
[1] Suitable for macroalgal coverage surveys.
[2] Suitable for macroinvertebrate surveys.

2.3.4. Drone selection

The following drones were identified as suitable for the macroalgal coverage survey:

- DJI Mavic 3M
- DJI Matrice 350

The following drones were identified as suitable for the macroinvertebrate survey:

- DJI Mavic 3 Pro
- DJI Mavic 4 Pro
- DJI Air 3S
- DJI Mini 4 Pro
- Autel Evo II Pro
- Autel Evo Nano

Of these drones, the DJI Mavic 3M and DJI Mavic 3 Pro had previously been purchased by UNSW and Sydney Water. As such, these drones were used for the ecological surveys.

2.4. Review of techniques to improve the methodology

2.4.1. Machine learning

Machine learning techniques, including Long Short Term Memory (LSTM) and Convolutional Neural Network (CNN) models, have been applied to aerial imagery for the purpose of vegetation classification. Review of these models identified that they require large volumes of labelled training data before they can perform effectively (e.g. Zhang et al., 2024; Miao et al., 2024). Training data is a time intensive activity and therefore there are limited efficiency benefits when only a small number of sites (e.g. ~10) are being assessed. The normalised difference vegetation index (NDVI) is well established as an efficient and simple metric for vegetation classification (Wardlaw et al., 2012). For this study it was determined that conventional thresholding of NDVI images offered a more robust and cost-effective method of outfall monitoring than the current machine learning techniques available.

2.4.2. Discussion of sensitivity in NDVI thresholds

While completing the present investigation, one important limitation of the previous study was identified. The NDVI images are not always directly comparable between impact and control sites, and even for images from the same site but captured on different dates. Each site appears to host distinct macroalgal communities with different spectral signatures which produce different NDVI values. NDVI thresholds for the analysis must be selected per image based on the type of vegetation present. While the analysis can determine a total macroalgal coverage, it will not necessarily distinguish between macroalgae types which must be assessed by an ecologist (Figure 2-4).

Figure 2-4 Macroalgal communities at Shellharbour, Long Reef, and Pheasant Point (left to right)

Initially, findings from Drummond and Howe (2018) indicated that a single generalised NDVI threshold may be suitable for all sites across all survey dates. In practice, following the expansion of the survey program across several new sites, the percent macroalgal coverage was found to be very sensitive to the NDVI threshold meaning each site required a specific threshold. Furthermore, the spectral signatures of some of the macroalgae communities change from green to brown due to desiccation when they are exposed at low tide. Figure 2-5 shows an example of the sensitivity analysis on the same rock platform for two different survey dates. The red squares show an appropriate NDVI threshold value, and the grey regions show the regions classified as 'vegetation' for each threshold value. Even a small change in the threshold value leads to misclassification.

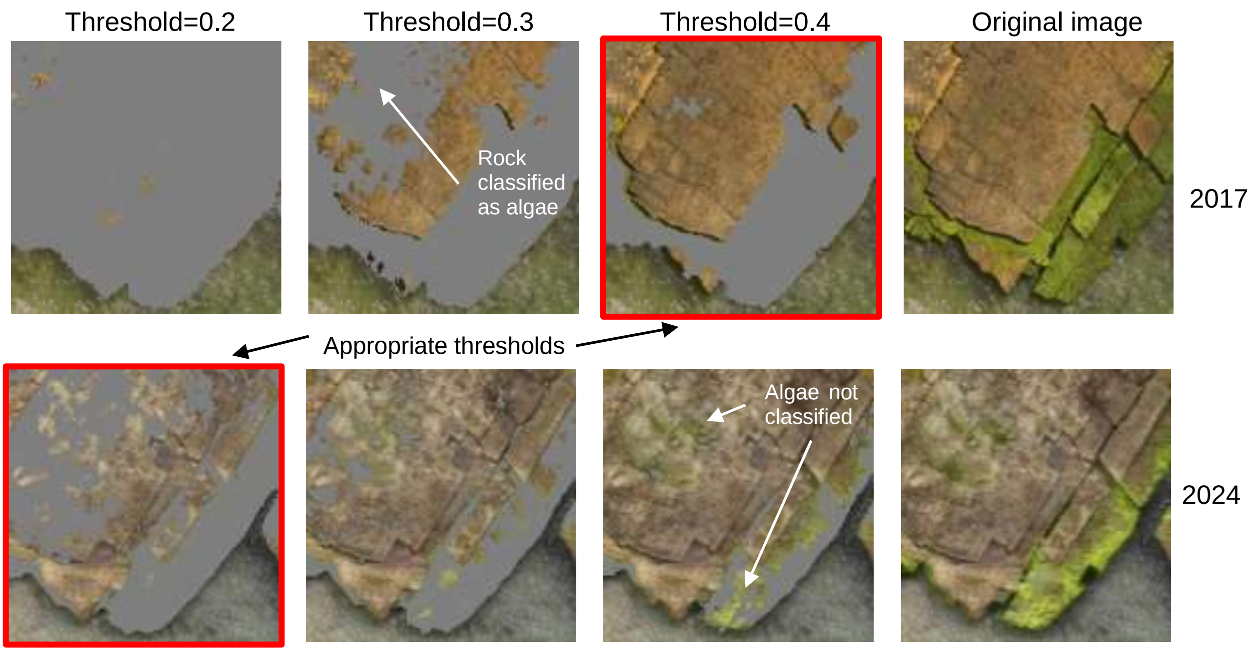


Figure 2-5 Sensitivity analysis for NDVI thresholds for surveys taken in 2017 and 2024

The NDVI classification is still useful (because it is simpler and faster than supervised RGB classification), but the appropriate vegetation threshold must be determined by an ecologist for each survey by careful examination of the RGB images. Note, during drone flights, multispectral imagery including near infrared (NIR) and RGB spectral bands are captured simultaneously, meaning no additional flights are required to obtain comparison imagery.

2.4.3. Future methodology development for consideration

Aerial and satellite imagery products are becoming increasingly available for use in applications such as ecological surveys. A range of products exists that include freely available data such as the Landsat and Sentinel satellite missions, and commercially available data such as Maxar, Planet Labs or Nearmap. All of these products provide imagery in the visible (red, green, blue) and near infrared bands that were utilised in this study.

Several limitations currently exist which mean that (for the time being) drone surveys remain the most suitable technology for the ecological assessment of intertidal rock platforms. These limitations include:

- Resolution of imagery is not suitable for macroinvertebrate surveys
- Resolution of free imagery (e.g. Landsat: 30 m and Sentinel: 10 m) is currently not detailed enough for the macroalgae coverage monitoring
- While resolution of commercial options may be sufficient for macroalgae monitoring (Maxar: 0.3 m, Planet Labs: 0.5 m, Nearmap: 0.3 m), they have other limitations:
  - Excessive costs compared to drone surveys
  - Satellite imagery can be impacted by cloud coverage
  - Available dates and times of imagery (e.g. at low tide)

In the future, as these technologies become more viable, further improvement such as real-time assessment of macroalgae coverage using satellite imagery may provide new insights into the health of rock platforms. This could be used to supplement existing drone surveys or replace the need for drone flights to measure macroalgae coverage.

3. Methods

3.1. Site selection

3.1.1. Overview

Intertidal rock surveys were required to assess potential impacts at three shallow water ocean outfall locations (i.e. Warriewood, Shellharbour and Bombo). Several control sites were required in addition to the impact sites immediately adjacent to the outfalls. Comparison between control sites and impact sites over time could then be used to identify potential influences from the ocean outfalls.

A minimum of two control sites were required for each of the impact sites. During previous surveys completed by Sydney Water (Sydney Water, 2024), some differences in tidal inundation were observed between the two control sites for Shellharbour that may impact rock platform habitat assemblages. Subsequently, it was decided that a third control site be identified for Shellharbour.

Sydney Water identified a range of preliminary impact and control sites for completing the surveys. Subsequently, a review of these locations was conducted, and additional locations were identified as required. The following sections outline the criteria considered for site selection (Section 3.1.2) as well as presenting the final sites chosen (Section 3.1.3).

3.1.2. Site selection criteria

The following site selection factors were identified to assist in determining suitable impact and control sites for the intertidal rock platform surveys:

- Proximity to the ocean outfall
- Wind data
- Wave data
- Ocean currents
- Elevation of rock platforms
- Proximity to other potential sources of water quality (e.g. lagoon entrances or pools)
- Flight restrictions

The most likely location for impacts to occur is the rock platforms immediately adjacent to the ocean outfalls. Impacts can be expected to reduce at locations further from the outfalls as the effluent mixes into the seawater.

The primary influences on transport of effluent from the shallow water outfalls is most likely to be driven by wind and nearshore waves. To a much lesser extent, the ocean current may also play a role in transport of pollutants. Wind data is available through the Bureau of Meteorology (BOM) stations located at Sydney Airport and Nowra (Figure 3-6). Nearshore wave data is available through Manly Hydraulics Laboratory with buoys located off Sydney and Port Kembla (Figure 3-7). Ocean currents can be observed from the NSW ocean reference station (IMOS, 2025). Wave and ocean current data indicate that energy during spring (when surveys would be completed) is predominantly from the south. Winds tend to be more variable in spring, switching from offshore in the morning to onshore in the afternoon. Together, this data indicates that effluent is most likely to travel in a northerly direction in spring, however, some variability is expected to occur.

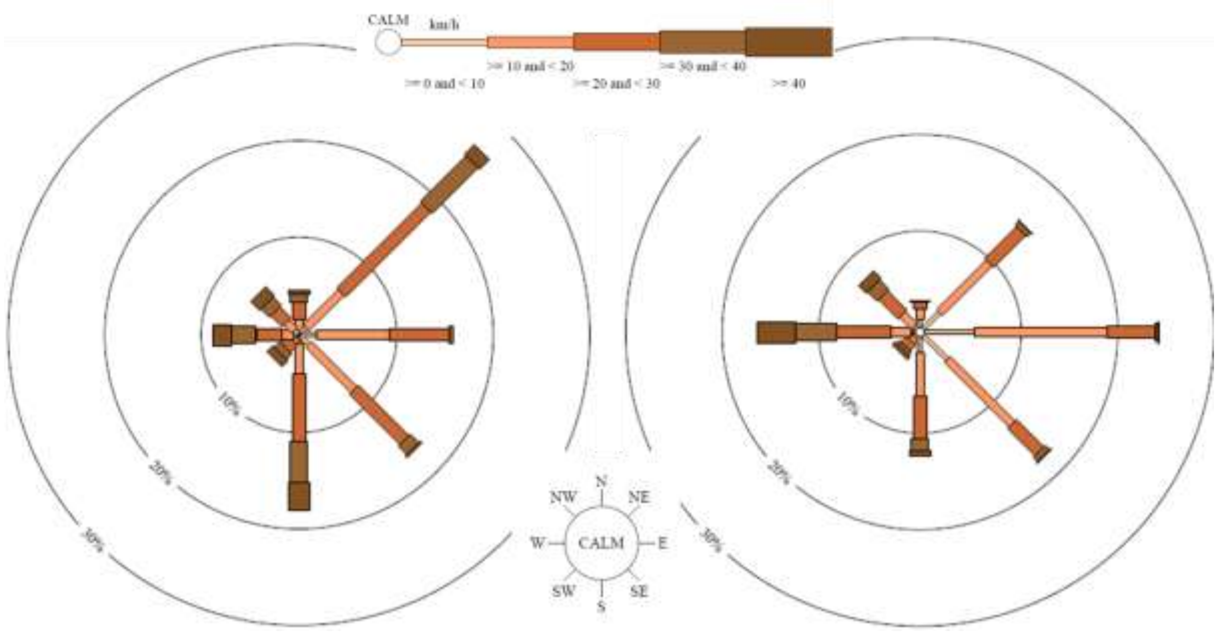


Figure 3-6 Wind rose for Sydney Airport (1939 to 2019) (left) and Nowra Airport (1955 to 2000) (right) for the average windspeed recorded at 3PM in spring (BOM, 2025)

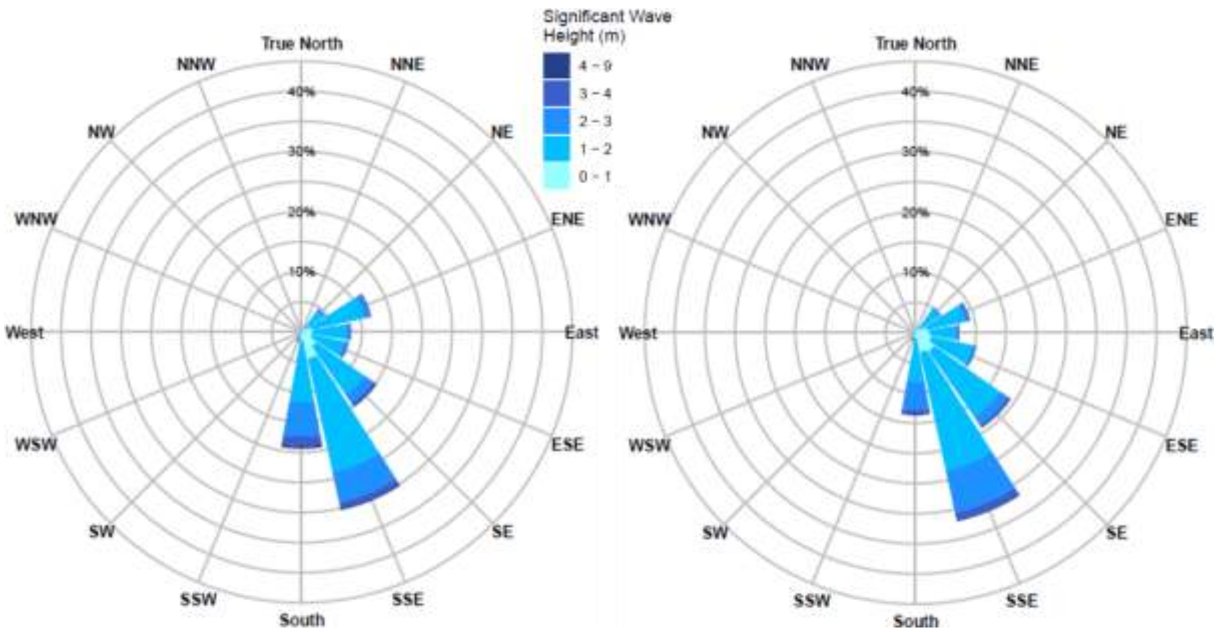


Figure 3-7 Significant wave height measured at the Sydney (1992 to 1010) (left) and Port Kembla (2012 to 2020) (right) offshore wave buoys during spring (MHL, 2025a; MHL, 2025b)

In addition to the forcing of waves and currents that could transport pollutants, several other factors were considered. The elevation of nearby rock platforms was a key consideration. It was important to ensure that control sites were at a similar elevation within the tidal range to impact sites so that habitat assemblages are similar. Potential other pollution sources were identified near some of the control sites, such as ocean pools or lagoon entrances, as was found to be the case at the Warriewood site (i.e. Narrabeen Lagoon and adjacent ocean pool). Finally, as a practical consideration, flight restrictions were considered. This affected site selection at Shellharbour where some sites close to Shellharbour Airport were not included as they were within flight routes and require stringent additional approvals to conduct surveys.

3.1.3. Site locations

Based on the criteria outlined in Section 3.1.2, 11 survey sites were identified including three impact sites and eight control sites (Figure 3-8 and Table 3-4 Impact and control site location and survey information). Impact sites were all identified near the outfall locations. Control sites were identified as the least likely to be impacted by outfalls (see Section 3.1.2) whilst being in regional proximity to the impact sites. Table 3-5 summarises the selection criteria for the control sites. Macroalgal coverage and macroinvertebrate surveys were conducted on five separate days in November and December 2024 by UNSW WRL and Sydney Water staff.

Maps of the individual survey sites are provided in Appendix A.

Figure 3-8 Site locations for Warriewood (left) and Shellharbour/Bombo (right)

Table 3-4 Impact and control site location and survey information

Impact/ Control	Location	Survey date(s)	Time	Latitude	Longitude	Tide	Survey area (ha)	Macroalgal survey flight duration (min)	Comments
Warriewood impact	Turimetta Headland (WW_OF)	14/11/2024* 26/11/2024	1:15 to 1:20pm* 1:45 to 2:00pm	-33.6969	151.3133	Low tide 1:49pm Low tide 11:59am	1.4	2 9	Surveys should be conducted during low tides (MLWS) to maximise rock exposure. A small falcon attacked the drone restricting the first survey
Warriewood control	Long Reef north (WW_REF1)	26/11/2024	10:50 to 11:35am	-33.7383	151.3137	Low tide 11:59am	4.8	15	
	Long Reef south (WW_REF2)	26/11/2024	12:20 to 12:35pm	-33.7428	151.3190	Low tide 11:59am	10.2	20	
	South Turimetta** (WW_REF3)	14/11/2024*	2:20 to 2:35pm	-33.7016	151.3096	Low tide 1:49pm	3.2	10	
Shellharbour impact	Barrack Point (SH_OF)	27/11/2024	1:45 to 2:00pm	-34.5611	150.8742	Low tide 12:51pm	2.0	8	Surveys should be conducted during low tides (MLWS) to maximise rock exposure.
Shellharbour control	Windang Island (SH_REF3)	27/11/2024	10:55 to 11:10am	-34.5464	150.8789	Low tide 12:51pm	2.4	9	
	Shellharbour Reserve (caravan park) north*** (SH_REF1)	27/11/2024	12:00 to 1:00pm	-34.5802	150.8756	Low tide 12:51pm	2.7	8	Combined macroalgal survey with Shellharbour Reserve south
	Shellharbour Reserve (caravan park) south*** (SH_REF2)	27/11/2024	12:00 to 1:00pm	-34.5802	150.8756	Low tide 12:51pm	2.7	8	Combined macroalgal survey with Shellharbour Reserve north
Bombo impact	Bombo headland (BO_OF)	27/11/2024	3:15 to 3:25pm	-34.6525	150.8633	Low tide 12:51pm	0.9	6	
Bombo control	Pheasant Point (BO_REF3)	28/11/2024	11:45am to 12:00pm	-34.6656	150.8569	Low tide 1:38pm	1.4	7	
	Bass Point north**** (BO_REF1)	12/12/2024	12:00 to 12:30pm	-34.5931	150.9005	High tide 12:42pm	3.3	9	Suitable for survey at high tide
	Bass Point south**** (BO_REF2)	12/12/2024	12:30 to 12:40pm	-34.5957	150.9027	High tide 12:42pm	1.6	12	Suitable for survey at high tide

* Method development trial day.
** South Turimetta was initially considered as a control site but discounted as it is likely impacted by Narrabeen Lagoon and the adjacent ocean pool. Drummond and Howe (2018) also noted this site had issues in terms of sand covering the rock platforms.

*** Existing control sites used by Sydney Water (Sydney Water, 2024; Sydney Water, 2023).
**** Bass Point may also be a suitable Shellharbour control site.

Table 3-5 Control site selection criteria

Outfall	Control site	Selection criteria	Notes
Warriewood	Long Reef north	South of outfall Similar elevation Suitable airspace	
	Long Reef south	South of outfall Similar elevation Suitable airspace	
	South Turimetta (not used)	South of outfall Similar elevation Suitable airspace	South Turimetta was initially considered as a control site but discounted as it is likely impacted by Narrabeen Lagoon and the adjacent ocean pool.
Shellharbour	Windang Island	Similar elevation Suitable airspace	Location is far enough north from the respective ocean outfalls that it is unlikely they to be impacted. Note, northern side of Windang Island likely to be impacted by Lake Illawarra.
	Shellharbour Reserve (caravan park) north	South of outfall Similar elevation Suitable airspace	Previous surveys completed by Sydney Water (Sydney Water, 2024) identified differences in tidal inundation between the two control sites for Shellharbour Reserve (north and south) that may impact rock platform habitat assemblages, hence the need to identify a third control.
	Shellharbour Reserve (caravan park) south	South of outfall Similar elevation Suitable airspace	As above.
Bombo	Pheasant Point	South of outfall Similar elevation Suitable airspace	
	Bass Point north*	Similar elevation Suitable airspace	Location is far enough north from the respective ocean outfalls that it is unlikely to be impacted.
	Bass Point south*	Similar elevation Suitable airspace	Location is far enough north from the respective ocean outfalls that it is unlikely to be impacted.

*Bass Point could also be a suitable control site for Shellharbour.

3.2. Field surveys and sampling

3.2.1. Macroalgae surveys

The objectives of the macroalgae pilot study were to:

- capture multispectral imagery of intertidal rock platforms using the DJI Mavic 3 Multispectral drone
- process imagery to estimate macroalgal percent cover using vegetation indices (e.g., normalised difference vegetation index (NDVI), normalised difference red edge index (NDRE))
- enable repeatable, scalable monitoring of macroalgal growth over time

Macroalgal cover was surveyed at each impact and control site (as outlined in Section 3.1) using automated drone flight transects. All flight transects were 100 m above ground level with 80% front and side overlap, flying at approximately 5 m/s using the in-built DJI flight software (DJI Pilot 2). Surveys were conducted using a DJI Mavic 3M equipped with the:

- Stock RGB Camera: 20 MP (5,280 x 3,956 image size, Field of View: 84° 24 mm), capturing red, green, and blue wavelengths with a 4/3 CMOS sensor
- Stock Multispectral Camera: 5 MP (2,592 x 1,944 image size, Field of View: 61.2° x 48.1° 25 mm), equipped with four 1/2.8-inch CMOS sensors capturing red, green, blue, red edge, and near-infrared (NIR) spectral bands.

Before automated flights, the drone was manually flown to the highest point of the nearest relevant cliff face to ensure that transects remained above the maximum cliff height (~40 m). The risk of gusts blowing the drone into the cliff face and the allowance of flights during windy conditions was reduced by ensuring cliff heights were well below the flight altitude (100 m).

To calibrate the multispectral imagery for consistency across sites and over time, a Sentera reflectance panel was used. The drone was held at waist height, capturing a still image of the panel before and after each flight, ensuring no shadows were cast over the panel or light sensors blocked on the drone. Automated transect flights covered 0.9 to 10 ha of rock platform per site and took 6 to 20 minutes to complete (see Table 3-6). SD cards were swapped between flights to avoid complete imagery loss in case of drone failure or loss.

Flights were conducted from the coastal platform, requiring particular care around overhanging cliffs during take-off and landing. At the Bombo site, the drone was launched from an elevated position 20 m above the rock platform, adjusting the automated flight altitude by subtracting 20 m to ensure consistency with other sites.

Further detail on the survey procedure is included in Appendix B.

3.2.2. Macroinvertebrate surveys

The objectives of the macroinvertebrate pilot study were to:

- capture standardised, high-resolution photo quadrats of intertidal rock platforms
- enable repeatable monitoring for ecological analysis (e.g., species cover, substrate type)
- compare the results from the pilot study to the traditional quadrat method using a high resolution SLR camera

High-resolution images of macroinvertebrates were captured at randomly distributed locations across the rock platforms for impact and control sites. For this the DJI Mavic 3 Pro with its 7X zoom RGB camera was used. The drone was manually flown above the rock platforms, pausing every few metres to capture still images. At each location the drone was navigated to 2 m above ground level using its bottom sensors for height estimation. The camera was zoomed to 3.5X and carefully focused before taking each image. This process was repeated up to 20 times per site, moving 2 to 3 m before repeating. While every effort was made to obtain a representative sample of the rock platform, wave action likely introduced a bias away from the platform edges, which were avoided to prevent damage or flooding of the drone.

Further detail on the survey procedure is included in Appendix B.

3.2.3. Water quality sampling

The objectives of the water sampling pilot study were to:

- collect water samples near the receiving water discharge point using a water sampling drone
- use the findings to develop a suitable method for future routine monitoring

Samples were collected from each impact and control location using a water sampling drone (DJI M350 RTK with a 1L Speedip payload).

Shellharbour and Bombo impact and control sites were sampled in February 2025 (except Pheasant Point control due to a technical issue) and the Warriewood impact and control sites sampled in June 2025. The primary purpose was to ensure that drone sampling would provide a safe, efficient, and repeatable method for collecting water samples. The secondary purpose was to conduct an initial assessment of the water quality and monitoring design.

The DJI M350 RTK drone, when integrated with the 1L Speedip payload, provides a safe, efficient, and repeatable method for collecting water samples from remote or hazardous aquatic environments. This method is particularly useful for environmental monitoring, water quality testing, and ecological research in areas such as reservoirs, wetlands, estuaries, and nearshore marine zones.

- DJI M350 RTK drone was deployed to collect a 1-litre water sample at each location using the Speedip payload (Figure 3-9). The drone was pre-programmed to fly to the outfall discharge location using precise GPS coordinates (RTK positioning). The sample container was lowered to approximately 0.5 m below the water surface (noting the highly variable water level due to tide and wave movement).

- To ensure sample integrity and minimise contamination the sample container was thoroughly cleaned between locations.
- Surface water quality samples were collected from all impact and control sites (with the exception of Pheasant Point control due to a technical issue), however not all control and respective outfall sites could be sampled on the same day. This was due to prioritisation given to site inspections and method development.

Further detail on the water sampling procedure is included in Appendix B.

Figure 3-9 DJI M350 RTK drone

3.2.4. Recommendations for future surveys

During field investigations a range of recommendations were identified to assist in future surveys of intertidal rock platforms:

- Warriewood and the Shellharbour impact sites should be surveyed when the tide level is close to Mean Low Water Springs (MLWS) to ensure the rock platforms are not submerged.
- Swell conditions should be monitored and wherever practical, surveys to be completed when swells are low (e.g. less than 1 m) to avoid whitewater reducing the available extent for image comparison. This can be checked on-site to ensure images are not adversely affected.
- Polarised filters could improve the macroinvertebrate photos, by reducing the effects of water reflection.
- Birds should be considered before conducting surveys. The surveys at Warriewood were interrupted by a small falcon. Larger birds including osprey were also observed, but they did not interfere with drone operations.
- Medical helicopter operations should be carefully monitored at sites located in hospital zones. Seaplanes should also be considered.

3.3. Macroalgae image processing

Images collected for the development of orthomosaics were processed using Pix4D Mapper software, under the ‘Ag Multispectral’ setting. A detailed guide on this procedure is provided in Appendix C. A range of rasters were developed per site which included:

- A digital surface model (DSM)
- Digital terrain model (DTM)
- Standard red, green, blue (RGB) visual orthomosaics
- Multispectral bands which included green, red, red edge, near infrared (NIR), normalised difference vegetation index (NDVI), and greyscale
- An additional five reflectance value orthomosaics

The multispectral bands were calibrated by assigning relevant reflectance factor coefficients to each band, as appropriate for the Sentera reflectance panel and DJI Mavic 3M drone. See Appendix C for detailed instructions.

3.4. Macroalgae coverage image analysis

Once orthomosaic imagery was developed for each of the study sites, image analysis was completed to determine the percentage coverage of macroalgae for a defined area on each rock platform.

The image analysis workflow consists of clipping and thresholding the NDVI images, then calculating zonal statistics inside the quadrats where they intersect with the raster data (Table 3-6). All the steps in the analysis workflow are routine procedures that can be completed in any geographic information system (GIS) software. QGIS was selected for this project because it is a free and open-source software program, as well as being user-friendly and easy to extend with custom Python scripts.

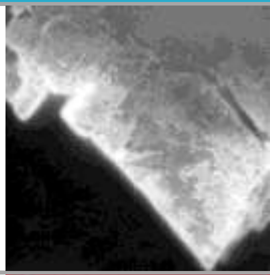
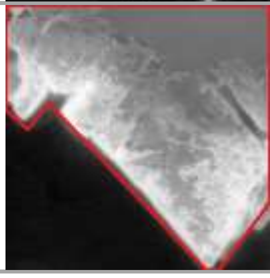
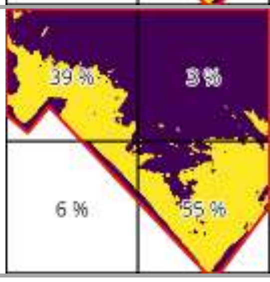
Two versions of the image analysis workflow were created for this project:

- QGIS extension ('Quadrat-coverage'), with a graphical user interface
- Python command line script ('quadrat-coverage.py'), for batch processing of multiple sites

Source code and documentation are available on GitHub (github.com/unsw-wrl/quadrat-coverage) and additional documentation is also provided in Appendix D.

Table 3-6 Image analysis workflow

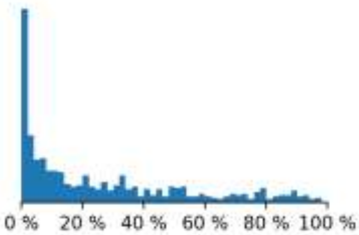
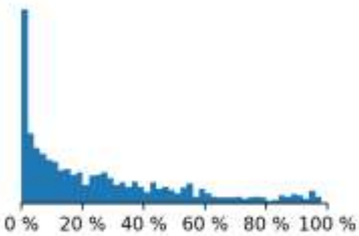
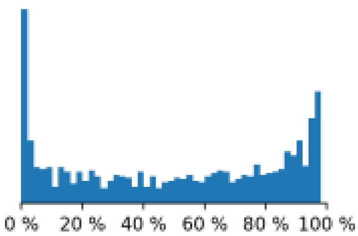
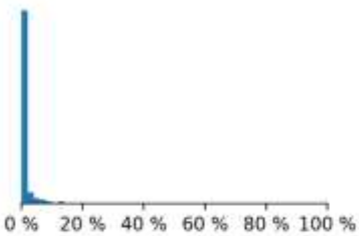
Step	Description	Example
1. Image collection and processing	Capture R, G, B, and NIR channels and process imagery into orthomosaics.	

Step	Description	Example
2. NDVI calculation	Calculate NDVI from R and NIR channels. The output is a greyscale image with values between -1 and +1 (higher values represent dense macroalgae).	
3. Clipping	Create clipping mask to remove unwanted regions (e.g. trees, shrubs, water).	
4. Thresholding	Determine appropriate NDVI threshold for classifying macroalgae. The output is a binary image: 1=macroalgae 0=other	
5. Quadrat generation	Divide region of interest into grid cells measuring 5 m x 5 m.	
6. Zonal statistics	Calculate the percent of macroalgae coverage in each quadrat.	

4. Macroalgae cover results

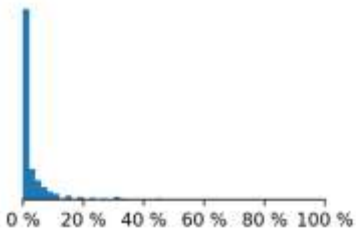
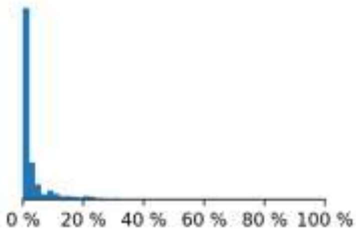
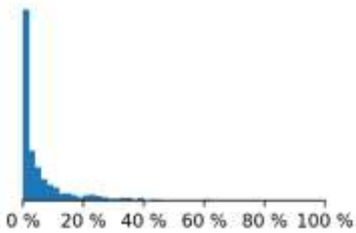
The results from analysis of the spring 2024 surveys in Warriewood, Shellharbour and Bombo are summarised in Table 4-7, Table 4-8 and Table 4-9 respectively. Note, coverage percentages cannot be simply compared between sites. Instead, changes in coverage should be assessed by comparing changes at individual sites over time (i.e. between each year that annual monitoring is conducted).

Table 4-7 Results of macroalgae cover analysis from Warriewood outfall

Site	Threshold[1]	Cover[2]	Histogram[3]	Example[4]
Warriewood Turimetta Headland (impact)	0.2	5%		
South Turimetta (control)[5]	0.3	8%		
Long Reef north (control)	0.4	27%		
Long Reef south (control)	0.4	<0.5%		

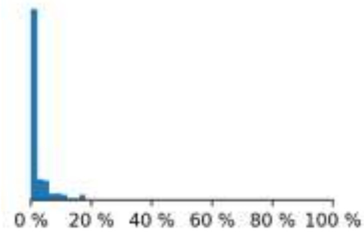
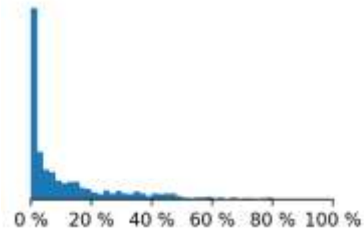
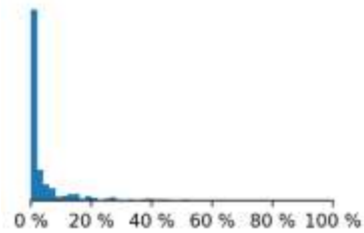
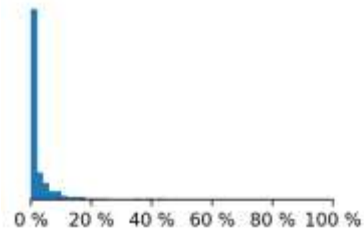
1. NDVI threshold used for analysis (values above this were classified as macroalgae).
2. Overall percent coverage of macroalgae within the region of interest (rounded to the nearest 1%).
3. Distribution of percent coverage by quadrat (ignoring quadrats with 0% cover).
4. Representative macroalgal coverage inside a 20 x 20 m region.
5. South Turimetta is likely impacted by Narrabeen Lagoon and the adjacent ocean pool which could skew results.

Table 4-8 Results of macroalgae cover analysis from Shellharbour outfall

Site	Threshold[1]	Cover[2]	Histogram[3]	Example[4]
Shellharbour Barrack Point (impact)	0.3	1%		
Shellharbour Reserve (north and south) (control)	0.1	1%		
Windang (control)	0.1	1%		

1. NDVI threshold used for analysis (values above this were classified as macroalgae).
2. Overall percent coverage of macroalgae within the region of interest (rounded to the nearest 1%).
3. Distribution of percent coverage by quadrat (ignoring quadrats with 0% cover).
4. Representative macroalgal coverage inside a 20 x 20 m region.

Table 4-9 Results of macroalgae cover analysis from Bombo outfall

Site	Threshold[1]	Cover[2]	Histogram[3]	Example[4]
Bombo Headland (impact)	0.2	<0.5%		
Bass Point north (control)	0.2	3%		
Bass Point south (control)	0.2	<0.5%		
Pheasant Point (control)	0.1	1%		

1. NDVI threshold used for analysis (values above this were classified as macrcoalgae).
2. Overall percent coverage of macroalgae within the region of interest (rounded to the nearest 1%).
3. Distribution of percent coverage by quadrat (ignoring quadrats with 0% cover).
4. Representative macroalgal coverage inside a 20 x 20 m region.

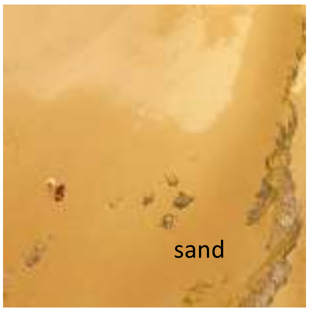
4.1. Discussion on image processing

Macroalgae coverage was analysed and assessed using an updated methodology based on Drummond and Howe (2018) with an improved workflow (see Section 3.4 and Appendix C). Data should be analysed over time (e.g. comparison between years) for the same aerial extent to ascertain if there are trends in macroalgae coverage.

It is important that an appropriate threshold value be determined for each survey by an ecologist through careful comparison of NDVI imagery to RGB imagery. This will ensure that if a different value is required between surveys (due to changes in environmental conditions), this is appropriately captured, and the images can be compared. Sensitivity testing identified that a change in NDVI threshold of ±0.05 could result in macroalgal coverage increasing or decreasing by 5 to 10%.

As noted by Drummond and Howe (2018), care should be taken when comparing surveys taken on different dates. For example, some rock outcrops at Warriewood are intermittently exposed during erosion and accretion cycles of the beach face. Furthermore, some rockpools and platforms are submerged or obscured by whitewater in certain conditions. As such, the clipping regions should exclude areas that cannot be directly compared (Table 4-10).

Table 4-10 Changes between surveys which prevent direct comparisons

Issue	2017	2024
Different sand cover		
Different water levels		

Note, this comparison was influenced by the long period between surveys (7 years) and ideally surveys are compared on an annual basis for the same extent. Significant changes in macroalgae coverage at an impact site compared to a control site could then be used as an indicator to trigger further investigations.

The analysis showed that it is difficult to accurately classify an entire site with a single threshold. Rather than trying to calculate the macroalgae coverage for the entire site, it is recommended to focus on a selection of key regions (as many as possible, to ensure statistical validity) which can be examined repeatedly for ongoing surveys (e.g. Figure 4-10). Focussing on small areas would allow thorough examination of the macroalgal communities using the RGB images and ensure that a suitable NDVI threshold is used when calculating the percent macroalgal coverage. The regions would ideally be located away from rockpools (the NDVI classification does not work well underwater), and towards the upper regions of the intertidal zone (where impacts from whitewater are minimal).

Figure 4-10 Examples of regions that might be suitable for direct comparison between surveys

5. Macroinvertebrate results

5.1. Overview

For the analysis of intertidal communities, the Sydney Water Aquatic Ecology group utilised a photo quadrat sampling technique to count individual biota and percentage cover. Image analysis software, ImageJ, was used to process images. The findings from the analysis will be used to determine the most suitable variables and settings to capture images using the DJI Mavic 3 Pro that can be processed in a lab setting.

The number of initial images collected by the DJI Mavic 3 Pro were taken based on the environmental factors on the day, and the technical constraints of the drone depending on the topography of each area. A total of 443 photos were taken across 12 sites, during the four days (Table 5-11).

Images from each site were reviewed by an ecologist in the lab to determine whether they could be processed using the ImageJ software. Learnings from the first survey were applied to subsequent surveys which improved the quality of the images, with 47% of images valid on the first survey (26 November), to mostly above 80% for the rest of the study.

Table 5-11 Drone images that were suitable for analysis

Site	Site code	Date sampled	Number of photos	Valid images	Photos analysed
Warriewood WRRF outfall (impact)	WW_OF	26/11/2024	34	74%	35%
Long Reef Headland North (control)	WW_REF1	26/11/2024	47	57%	19%
Long Reef Headland South (control)	WW_REF2	26/11/2024	38	47%	28%
Turimetta Beach South (control)	WW_REF3	26/11/2024	33	85%	18%
Shellharbour WRRF outfall (impact)	SH_OF	27/11/2024	31	90%	18%
Shellharbour Reserve North (control)	SH_REF1	27/11/2024	62	98%	8%
Shellharbour Reserve South (control)	SH_REF2	27/11/2024	27	93%	20%
Windang Island (control)	SH_REF3	27/11/2024	37	84%	16%
Bombo WRRF outfall (impact)	BO_OF	27/11/2024	27	82%	23%
Bass Point North (control)	BO_REF1	12/12/2024	37	81%	17%
Bass Point South (control)	BO_REF2	12/12/2024	35	91%	16%
Pheasant Point (control)	BO_REF3	28/11/2024	35	74%	19%

The images chosen to be analysed were randomly selected based on features of the area and the total amount of photos taken per site. Observations were made by an ecological analyst in the lab for each site, to determine biological conformity, correct placement of drone in the intertidal zone, and techniques to reduce the anomalies made by the drone itself.

5.2. Observations

5.2.1. Warriewood impact

Dimensions and scale of the drone photos varied over the 34 photos taken. Over-exposure from direct sunlight impacted the analysis of some images. Photos with moving water also made it difficult to identify certain specimens. Drone stability also impacted image resolution. A larger genus of barnacle was present at this site. Communities sparsely covered the area, with rock limpets being the dominant species.

5.2.2. Long Reef controls (North and South)

Neptunes necklace was the dominant species at the Long Reef North control site, having greater than 84% coverage in some areas. Due to their size, the drone images clearly captured rock limpets, having a count of ~200 in some images. Only 57% of the photos at the Long Reef North site were useable, with most blurry due to intense reflection making it difficult to count communities.

The Long Reef South control site had similar image quality challenges to Long Reef North, with only 47% of images suitable due to intense reflection and blurriness. Many images were also collected outside the intertidal zone. Community diversity was therefore reduced, and low counts of rock limpets (~40), and barnacles were present. It is recommended that an ecologist accompany the field drone operator to determine the most suitable habitat/location at which photos should be taken (i.e. appropriate intertidal line). Once drone operator is familiar with locations, habitats, and photograph quality requirements, this may not be required for future surveys.

5.2.3. South Turimetta Beach control

Many photos taken at South Turimetta Beach were too high up the rock platform and outside the intertidal zone. While 85% of images were able to be used, the instability of the drone and the over-exposure made it difficult to count the macroinvertebrates present. The structure of limpets and barnacles were difficult to separate and assess. The species that dominated the area were: rock limpets, oyster borers, barnacles, with the presence of Neptunes necklace.

Note, South Turimetta Beach has been excluded for future surveys due to the potential to be impacted by Narrabeen Lagoon and the adjacent ocean pool.

5.2.4. Shellharbour controls (North Reserve and South Reserve) and impact

The two Shellharbour control sites at the caravan park reserve, and the impact site at Barrack Point had the highest percentage of valid images taken by the drone. 120 photos were taken collectively, with valid images ranging from 90-98%. Unfortunately, most of these images were taken too high up the rock platform and did not correspond with the area used in traditional monitoring program. This was reflected in the lower presence and abundance of periwinkles, and the sparseness of community compared to historical data. As such, it is recommended that an ecologist accompany the field drone operator to determine the most suitable habitat/location at which photos should be taken (i.e. appropriate intertidal line). Once the drone operator is familiar with locations, habitats, and photograph quality requirements this may not be required for future surveys.

Images taken near the intertidal zone at the impact site had greater than 50% moving water within the image making analysis difficult. Due to Shellharbour's overall diversity, the photos taken identified macroinvertebrates commonly seen from traditional routine surveys.

5.2.5. Windang Island control

31 out of 37 images were valid for analysis at Windang Island. However the surveys were too far up the platform i.e. outside the intertidal zone, and the focus setting on the drone camera did not stabilise sufficiently to capture macroinvertebrates clearly. This resulted in only 16% of the photos being analysed, the second lowest percentage of images able to be analysed across all sites. Periwinkles were present in large numbers, with *Bembicium*, *Austrococchlea*, *Nerita*, and rock limpets also present within the intertidal community.

5.2.6. Bombo impact

Periwinkles dominated most images taken at the Bombo impact site, ranging from a count of 22 to 175 per photo. In one photo, a smaller and hardier species of barnacle dominated the area with a count of 330 specimens. Although 82% of the images were suitable for analysis, the location of the surveys and the stability in focusing the drone camera made the areas selected not ideal for analysis. There were instances where 50-100% of the images consisted of moving water (made from the downward draft of the propellors), and images were slightly blurry. The communities present also reflect the drone being too far up the rock platform.

5.2.7. Bass Point controls (North and South)

For both Bass Point control sites (North and South), images taken were too far up the rock platform i.e. outside the intertidal zone. Both sites consisted of barnacle communities, but due to the distance from the ground, and genera present, they were difficult to distinguish from one another. In some cases, counts were not able to be completed due to images being blurry. There was also intense reflection at the site, with some images covered in greater than 50% water which made it difficult for analysis.

It is recommended that an ecologist accompany the field drone operator to determine the most suitable habitat/location that photos should be taken (i.e. appropriate intertidal line) for future surveys. Once the drone operator is familiar with locations, habitats, and photograph quality requirements this may not be required for future surveys.

5.2.8. Pheasant Point control

Compared to all other locations, Pheasants Point had the simplest community with minimal diversity. Periwinkles ranged from a count of 13 to 291, with only four to five other hardier biota present on the platform. Most images taken captured sand spread across the site, which may indicate sampling was undertaken higher up the platform. Most images captured were blurry, with less than 50% moving water in each image. Variability in the distance from the ground and the drone positioning was also prevalent, making the area of analysis inconsistent, and therefore not comparable in some cases.

5.3. Comparison between DJI Mavic 3 Pro and mirrorless interchangeable lens camera (MILC)

A small study was conducted to compare images taken by the DJI Mavic 3 Pro and the routinely used handheld Sony ILCE-6000, which is a compact, high-resolution mirrorless digital camera featuring a 24.3 effective megapixel APS-C sensor. Three images were used to determine if picture quality would affect the analysis phase. For consistency, one analyst went through all images taken for the study.

Two pictures were taken at a known site, of known diversity (Shellharbour), the third, at a new site, Windang Island. Each photo from the drone and Sony ILCE-6000 were taken on the same day and time to reduce variability.

The results of the analysis comparing both the drone and Sony ILCE-6000 images analysed using ImageJ are summarised in Table 5-12.

Table 5-12 Comparison between the drone and Sony ILCE-6000 total count and % cover results using Image J analysis

Site	Bembicium (count)	Austrocochlea (count)	Rock Limpet (count)	Oyster borer (count)	Nerita (count)	Red Algae (% cover)	Neptunes necklace (% cover)	Waratah anemone (count)
Shellharbour 2A Sony	9	13	7	5	3	0	10.8	2
Shellharbour 2A Drone	9	8	4	1	2	0	10.6	0
Shellharbour 2B Sony	0	10	1	1	24	0	30.4	0
Shellharbour 2B Drone	0	9	0	1	23	0	30.2	0
Windang Sony	11	61	15	2	12	39.3	0	0
Windang Drone	9	54	5	2	10	39.1	0	0

*Only taxa present within images are presented, other taxa surveyed for were absent from all images.

The above comparison shows that the larger macroinvertebrates (Bembicium) had comparable counts between the drone and Sony SLR using Image J analysis.

Austrocochlea, Rock limpets, Oyster borers, and Waratah sea anemones were biota that were missed using the drone compared to the hand held SLR camera (Table 5-12). This was due to the downward wind produced by the propellors of the drone making ripples on the surface of the rock pools (Figure 5-11). This impaired analysis, resulting in a loss of diversity for the drone images. Counts of larger static biota (Neptunes necklace), were similar in percentage area cover with a difference of 0.1-0.3%.

During ImageJ analysis, an analyst can slightly manipulate the image manually (lighting, contrast), to help aid in the count of biota. When analysing the Windang Island images (Figure 5-12), the molluscs that were discerned by the Sony ILCE-6000 were not seen by the drone (crevasses) - this is mainly due to loss of structure, and lower pixelation of the drone camera. This was most common when counting smaller invertebrates, such as barnacles (and their colonies), and periwinkles at other sites. This impacted the count for each image captured by the drone.

Figure 5-11 Shellharbour image comparing Sony ILCE-6000 image (left) and drone image (right)

Figure 5-12 Windang Island images comparing Sony ILCE-6000 image (left) and drone image (right)

6. Water quality sampling results

The DJI M350 RTK with the 1L Speedip payload (Figure 3-9) was found to offer a reliable and precise method for aerial water sampling. This approach improves safety, reduces field time, and enables access to otherwise difficult or hazardous sampling locations. With proper planning and handling, it supports high-quality environmental data collection for research and regulatory compliance.

Water samples were collected from all impact and control locations between February 2025 and June 2025 (except for Pheasant Point control due to a technical issue with the drone). The results are presented in Table 6-13 and Table 6-14.

The results show that physico-chemical and metal concentrations were comparable between the outfall and control locations, with most of the metal results below the laboratory limit of reporting. Nutrient concentrations were higher at the impact site, which was not unexpected noting the sample collection design flaw described below.

Overall, this pilot program provided a snapshot (one sample per location) of the water quality at each location to test the concept and suitability of using a drone to collect water samples. More data is required to derive any meaningful conclusions from the water quality results.

It is important to note that a sample design flaw was identified during the drone water sampling pilot study in that the impact samples were collected at the actual outfall discharge point, and did not take into consideration the extent of the mixing zone. As such the impact site results should not be compared with guidelines and should be viewed with caution.

A recommendation for future sampling is to understand the mixing zone for each impact site and collect a minimum of two samples at the edge of the mixing zone. To investigate this further, Sydney Water will increase the spatial spread of samples at the Shellharbour and Bombo outfall locations for the 2025-26 monitoring period (Figure 6-13). Site specific limitations need to be investigated at the Warriewood site before additional spatial sampling can be accommodated.

Figure 6-13 Proposed Shellharbour and Bombo outfall site water quality sampling locations for 2025-26

Table 6-13 Physico-chemical and nutrient water quality results collected using the water sampling drone at the outfall discharge location and control sites

		Ammonia nitrogen	Oxidised nitrogen	Total nitrogen	Soluble reactive phosphorus	Total phosphorus	Salinity	pH	Turbidity
Sampling Point	**Sampling Point Description**	mg/L	mg/L	mg/L	mg/L	mg/L	ppt	pH Units	NTU
SH_OF	**Shellharbour WRRF outfall at Barrack Point**	**0.02**	**0.19**	**0.33**	**0.058**	**0.088**	**35.4**	**8.16**	**0.6**
SH_REF1	Shellharbour Reserve North - Shellharbour Control	0.01	<0.01	0.15	0.002	0.013	35.6	8.19	0.3
SH_REF2	Shellharbour Reserve South - Shellharbour Control	0.01	<0.01	0.13	0.003	0.013	35.6	8.21	0.7
SH_REF3	Windang Island - Shellharbour Control	<0.01	0.02	0.28	0.007	0.021	35.6	8.14	0.7
BO_OF	**Bombo WRRF outfall**	**0.02**	**0.02**	**0.27**	**0.053**	**0.075**	**35.2**	**8.15**	**0.8**
BO_REF1	Bass Point North - Bombo Control	0.01	<0.01	0.13	0.003	0.007	35.8	8.14	0.3
BO_REF2	Bass Point South - Bombo Control	0.01	<0.01	0.20	0.003	0.009	35.6	8.13	0.2
WW_OF	**Warriewood WRRF outfall**	**0.03**	**0.06**	**0.24**	**0.014**	**0.020**	**36.4**	**8.04**	**0.4**
WW_REF3	Turimetta Beach South - Warriewood Control*	0.01	0.04	0.16	0.009	0.016	36.3	8.03	0.4
WW_REF2	Long Reef Headland South - Warriewood Control	0.01	0.03	0.14	0.007	0.014	36.5	8.16	0.4
WW_REF1	Long Reef Headland North - Warriewood Control	0.01	0.03	0.15	0.006	0.011	36.4	8.16	0.6

* South Turimetta was initially considered as a control site but discounted as it is likely impacted by Narrabeen Lagoon and the adjacent ocean pool. Drummond and Howe (2018) also noted this site had issues in terms of sand covering the rock platforms.

Note: the results do not allow for the mixing zone and therefore over represent concentrations. Hence they should be viewed with care. The design of the water sampling program will be revisited in 2025-26

Table 6-14 Metals water quality results collected using the water sampling drone at the outfall discharge location and control sites

Sampling Point	Sampling Point Description	Filterable aluminium ug/L	Total aluminium ug/L	Filterable cobalt ug/L	Total cobalt ug/L	Filterable copper ug/L	Total copper ug/L	Filterable nickel ug/L	Total nickel ug/L	Filterable zinc ug/L	Total zinc ug/L
SH_OF	**Shellharbour WRRF outfall at Barrack Point**	**<5**	**9**	**<0.1**	**<0.1**	**0.6**	**0.6**	**<0.2**	**0.2**	**<1**	**<1**
SH_REF1	Shellharbour Reserve North - Shellharbour Control	<5	<5	<0.1	<0.1	1.7	1.7	<0.2	<0.2	<1	<1
SH_REF2	Shellharbour Reserve South - Shellharbour Control	<5	7	<0.1	<0.1	0.6	0.6	<0.2	<0.2	<1	<1
SH_REF3	Windang Island - Shellharbour Control	6	7	<0.1	<0.1	0.6	0.6	<0.2	<0.2	<1	<1
BO_OF	**Bombo WRRF outfall**	**<5**	**8**	**<0.1**	**<0.1**	**<0.5**	**<0.5**	**<0.2**	**<0.2**	**<1**	**<1**
BO_REF1	Bass Point North - Bombo Control	<5	<5	<0.1	<0.1	<0.5	<0.5	<0.2	<0.2	<1	<1
BO_REF2	Bass Point South - Bombo Control	<5	<5	<0.1	<0.1	<0.5	<0.5	<0.2	<0.2	<1	<1
WW_OF	**Warriewood WRRF outfall**	**<5**	**<5**	**<0.1**	**<0.1**	**<0.5**	**<0.5**	**<0.2**	**<0.2**	**<1**	**<1**
WW_REF3	Turimetta Beach South - Warriewood Control*	<5	<5	<0.1	<0.1	<0.5	<0.5	<0.2	<0.2	<1	<1
WW_REF2	Long Reef Headland South - Warriewood Control	<5	<5	<0.1	<0.1	<0.5	<0.5	<0.2	<0.2	<1	<1
WW_REF1	Long Reef Headland North - Warriewood Control	6	9	<0.1	<0.1	<0.5	<0.5	<0.2	<0.2	<1	<1

* South Turimetta was initially considered as a control site but discounted as it is likely impacted by Narrabeen Lagoon and the adjacent ocean pool. Drummond and Howe (2018) also noted this site had issues in terms of sand covering the rock platforms.
Note: the results do not allow for the mixing zone and therefore over represent concentrations. Hence they should be viewed with care. The design of the water sampling program will be revisited in 2025-26

7. Conclusion

7.1.1. Overview

The pilot study trialled using drones to survey macroalgae cover and macroinvertebrates on intertidal rock platforms adjacent to nearshore ocean outfalls, and to collect water samples adjacent to the rock platforms. This is consistent with the recommendations provided by van Dam et al (2023) following the STSIMP review in 2021-2022. The methods incorporate novel remote sensing techniques and improve safety by reducing the need for personnel to access coastal rock platforms and turbulent receiving waters.

7.1.2. Locations

The identified outfall and respective control locations were found to be suitable for future macroalgae and macroinvertebrate surveys. The only exception was South Turimetta Beach which is potentially impacted by Narrabeen Lagoon and the adjacent ocean pool.

The water sampling sites at the impact locations did not consider the extent of the mixing zone. As such, the results from these locations will be over representative and should be viewed with care. It is recommended that future water sampling at the impact sites take the mixing zone into consideration and include a minimum of two samples. The water sampling sites at the control locations are suitable for future water monitoring.

7.1.3. Macroalgae surveys

Building on the work of Drummond and Howe (2018), macroalgae cover surveys were trialled across a broader range of sites (11 in total). Opportunities to further improve on this previous method, including post processing techniques, were also tested.

Incorporation of machine learning to further improve the analysis was investigated, however, due to the scale of the investigation it was not recommended (the effort required to train a model with a sufficiently large number of labelled images is not likely to be cost effective). New technologies, such as satellite and aerial imagery, were also investigated. It was found that further advancements in these technologies are required before they become cost effective for monitoring intertidal rock platforms.

Key findings regarding the suitability of drone technology and post processing techniques used in this study for macroalgae coverage surveys are summarised in Table 7-15.

Table 7-15 Suitability of automated macroalgae quantification using different image products

	RGB	NDVI
Suited for small regions	✔	✔
Suited for entire survey sites	✘	✘
Works in submerged areas	✔	✘
Uses simple threshold-based classification	✘	✔
Can re-use classifier across different survey dates	✘	✘

This investigation identified that it was not possible to develop a completely automated system for classifying and quantifying macroalgae coverage because of the sensitivity and subjective nature of NDVI thresholding. Instead, it is recommended that RGB images be carefully examined by a suitably qualified ecologist to ensure the NDVI images are interpreted correctly (i.e. thresholds are appropriately chosen). In this way, the macroalgal coverage surveys can be used as a supplementary tool to assist ecologists in assessing the condition of rock platform surveys. Macroalgal coverage surveys form one line of evidence for consideration by ecologists when assessing the health of intertidal rock platforms, however, results from this method should be carefully considered alongside other lines of evidence, such as the macroinvertebrate surveys.

The DJI Mavic 3 Multispectral drone was found to be suitable for monitoring macroalgal growth on intertidal rock platforms. However, as outlined above, there are limitations with the method. As such, further work is required to determine the long-term suitability of the macroalgae survey method.

7.1.4. Macroinvertebrate surveys

The suitability of using drones for macroinvertebrate surveys was trialled at all sites. The method involved capturing high-resolution images using drones for later post processing by a suitably experienced ecologist. This method was successful in removing the requirement for ecologists to access rock platforms, improving the safety of completing this survey. However, there were limitations to this method including:

- inability to move or look underneath algae and rock ledges which occur within the survey area
- image resolution
- water reflection within imagery

While the DJI Mavic 3 Pro had an inbuilt camera with 48 MP, the smaller macroinvertebrates were difficult to identify. A comparative analysis with images taken from a Sony ILCE-6000 showed a difference in detection of specific taxa, primarily caused by drone interference (i.e. propellors causing water movement) and image quality. A higher resolution camera may address this issue. Undertaking surveys at low tides, combined with low swell conditions, will also assist in obtaining the best images for macroinvertebrate analysis.

Based on the learnings from the 2024-25 pilot study, it is recommended to:

- trial using the DJ Mavic 4 Pro which has a greater resolution capability (100 MP) and zoom options
- have an ecologist accompany field drone operator to determine the most suitable habitat/location that photos should be taken (i.e. appropriate intertidal line). Once the drone operator is familiar with locations, habitats, and photograph quality requirements this may no longer be necessary
- collect images using the same height and camera settings to maintain consistent image quality
- set the drone at a height that reduces/removes the water rippling affect caused from the downward wind from the drone propellers

- avoid areas where there is water movement due to wave wash (consider tide changes)
- look at options to assess photo quality on-site
- schedule sampling trips to align with suitably low tides, particularly for Bombo
- avoid taking images when the sun is directly above the drone as this will lead to increased reflection and/or over exposure of images
- trial using ND and UV filters to reduce glare/ reflectance during sunny days
- undertake more comparison studies between the drone images and images from the handheld Sony ILCE-6000 to assist in validation of the method

7.1.5. Water quality assessment

Water samples were successfully collected at all locations (except Pheasant Point due to technical issues) using the DJI M350 RTK with the 1L Speedip payload. This technique allowed for samples to be collected from wave impacted turbulent conditions adjacent to rocky platforms and/or cliffs, which has not previously been possible due to safety concerns.

While samples were able to be collected from most locations, future refinement of the method is recommended, including:

- understand the mixing zone for each impact site
- collect a minimum of two samples from the impact sites at the edge of the mixing zone

Overall, more data is required to derive any meaningful conclusions from the water quality results.

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Appendix A Site locations

Figure A-1 Warriewood impact site (Turimetta Headland)

Figure A-2 Warriewood control sites (Long Reef, north and south)

Figure A-3 Warriewood control site (South Turimetta Beach) deemed unsuitable due to the impact from Narrabeen Lagoon, the rockpool/baths and sand inundation for some of the rock platforms

Figure A-4 Shellharbour impact site (Barrack Point)

Figure A-5 Shellharbour control site (Windang)

Figure A-6 Shellharbour control site (Shellharbour Reserve, separated into north and south for macroinvertebrate surveys, combined as one site for the macroalgal survey)

Figure A-7 Bombo impact site (Headland)

Figure A-8 Bombo control site (Pheasant Point)

Figure A-9 Bombo control sites (Bass Point, north and south)

Appendix B Survey and sampling procedures

B1 Macroalgae surveys

B.1.1 Equipment and software

Hardware trialled included:

- Drone: DJI Mavic 3 Multispectral
- Sensors: 5-band multispectral camera (Green, Red, Red Edge, NIR, RGB)
- Accessories: RTK module (for high-accuracy positioning), spare batteries, SD cards

Software

- Flight Planning: DJI Pilot 2/ AVCRM
- Processing: Pix4Dmapper, QGIS
- Analysis: ImageJ or custom Python scripts for vegetation index calculation

B.1.2 Site selection and set up

Site selection

- Select intertidal zones with known or suspected macroalgal presence.
- Schedule flights during low tide and clear weather for optimal visibility and safety.
- Ensure minimal water pooling to reduce reflectance interference.

Preflight setup

- Conduct a risk assessment and log mission in the drone management system.
- Calibrate the multispectral sensor using the reflectance calibration panel before flight.

Flight parameters

- Altitude: 80m (10–20 meters) AGL (adjust based on desired GSD and coverage)
- Flight Mode: Grid mission (automated)
- Lighting: Midday flights preferred to minimize shadowing

B.1.3 Image capture and data collection

- Launch the drone and execute the pre-programmed flight path.
- Ensure all five spectral bands are captured for each image.
- Monitor live feed for anomalies (e.g., glare, water reflection).
- Land and safely store data on SD cards.

B.1.4 Post-processing workflow

Image processing

- Import images into Pix4Dmapping
- Generate orthomosaic and reflectance maps for each band.
- Apply radiometric correction using calibration reflectance panel data.

Macroalgal percent cover estimation

- Use QGIS to classify pixels based on index thresholds (e.g., NDVI > 0.2 = algae).
- Calculate percent cover per quadrat or area of interest.
- Export results as maps, tables, or shapefiles.

B.1.5Quality control and validation

- Ground-truth selected quadrats using physical surveys or high-resolution RGB imagery.
- Compare drone-derived estimates with manual observations to validate accuracy.

B.1.6 Best practices and considerations

- Avoid flights during high glare or wet surfaces.
- Use consistent flight parameters for time-series comparisons.
- Regularly calibrate sensors and validate index thresholds.

B2 Macroinvertebrate surveys

B.2.1 Equipment and software

Hardware trialled included:

- Drone: DJI Mavic 3 Pro
- Camera: Integrated Hasselblad camera with optical zoom
- Accessories: Spare batteries, SD cards, tablet or smartphone
- Optional: Ground markers (PVC quadrat frames), RTK module
- Software: DJI Fly app, ImageJ, QGIS, (for analysis)

B.2.3 Site selection and set up

Site selection and timing

- Choose intertidal zones with ecological interest and safe access.
- Conduct surveys during low tide to maximize exposure of rock platforms.
- Mark quadrat locations with visible frames if needed.

Pre-flight setup

- Conduct a risk assessment and plan mission in the drone management system.
- Set flight mode to Cine for stable, slow movement.

Camera configuration

- Altitude: 2.2 meters AGL using obstacle avoidance sensor
- Zoom: Use optical zoom to frame a 0.5 m × 0.5 m or 1 m × 1 m quadrat.
- Gimbal: 90° downward (nadir)
- Photo Mode: JPEG /Auto/Explore mode
- White Balance: Manual (based on lighting)
- Focus: Tap-to-focus or manual

Quadrat capture procedure

- Fly to the quadrat location, hover at 2.2 m AGL and use explore mode to zoom 3.5x
- Use the live feed and zoom to centre and frame the quadrat
- Capture 1 image per quadrat.
- Record metadata:
- GPS coordinates
- Quadrat ID
- Time and date
- Zoom level
- Repeat for all quadrats.

B.2.4 Post-flight workflow

Data management

- Download and organize images by site and quadrat ID.
- Rename files for traceability

Backup and storage

- Store images on both local and cloud-based systems.

Image analysis

- Use software such as:
- ImageJ for percent cover and object counting
- QGIS for spatial mapping

B.2.5 Best practices and considerations

- Fly in calm weather to maintain stability at low altitude.
- Use a tablet for better visibility and framing.
- Conduct test flights to calibrate zoom and framing.
- Consider RTK positioning for high-accuracy geolocation.

B3 Water sampling procedure

B.3.1 Equipment and software

Hardware

- Drone: DJI Matrice 350 RTK
- Payload: Speedip 1L water sampler (integrated with DJI SkyPort or custom mount)

Software

- Flight Planning: DJI Pilot 2/ AVCRM

B.3.2 Site selection and set up

Pre-flight preparation

Site assessment

- Identify sampling locations using Nearmap or field reconnaissance.
- Ensure safe take-off/landing zones and assess environmental risks (e.g., wind, birds, obstacles).

Regulatory compliance

- Confirm CASA flight permissions.
- Conduct a risk assessment and plan mission in the drone management system.

Equipment check

- Inspect drone, payload, and sampling bottles.
- Calibrate RTK system for precise geolocation.
- Ensure Speedip payload is clean and securely mounted.

B.3.3 Flight and sampling procedure

Step 1: Mission planning

- Program waypoints or manual flight path to each sampling location.
- Set altitude for transit (e.g., 10–20 m AGL) and descent to sampling height (just above water surface).

Step 2: Sampling execution

- Fly to the sampling point.
- Descend slowly to the water surface (typically 3 m above).
- Activate the Speedip payload to lower the sampling container to 0.5m below the surface.
- Wait for the container to fill.
- Retract the sampler and ascend to transit altitude.
- Return to base or proceed to the next sampling point.

Step 3: Sample handling

- Land the drone and carefully remove the filled container and pour into jug. Repeat step 2 if more sample volume is required. Follow Sydney Water aseptic techniques.
- Label the bottle with:
- Sample ID
- GPS coordinates
- Date and time
- Store in a cooler or appropriate container for transport.

B.3.4 Post-flight workflow

Sample analysis

- Deliver samples to the lab for testing (e.g., pH, turbidity, nutrients, contaminants).
- Record results in a central database for reporting and trend analysis.

B.3.5 Best practice and considerations

- Avoid sampling during high wind or wave conditions.
- Clean the Speedip payload between sites to prevent cross-contamination.

Appendix C Pix4D image processing guide

C1 Overview

The following section provides a step-by-step guide for using Pix4D Mapper software to process drone imagery. Note, Pix4D is a commercial image processing software built to process drone imagery. Software can be purchased and downloaded from: https://www.pix4d.com/.

C2 Setting up a project

Once Pix4D Mapper has been opened the first step is to create a New Project. Following this:

- Give the project a name – “Name”
- Select location for project to be saved – “Create In”
- Select “next” (Figure C-1)

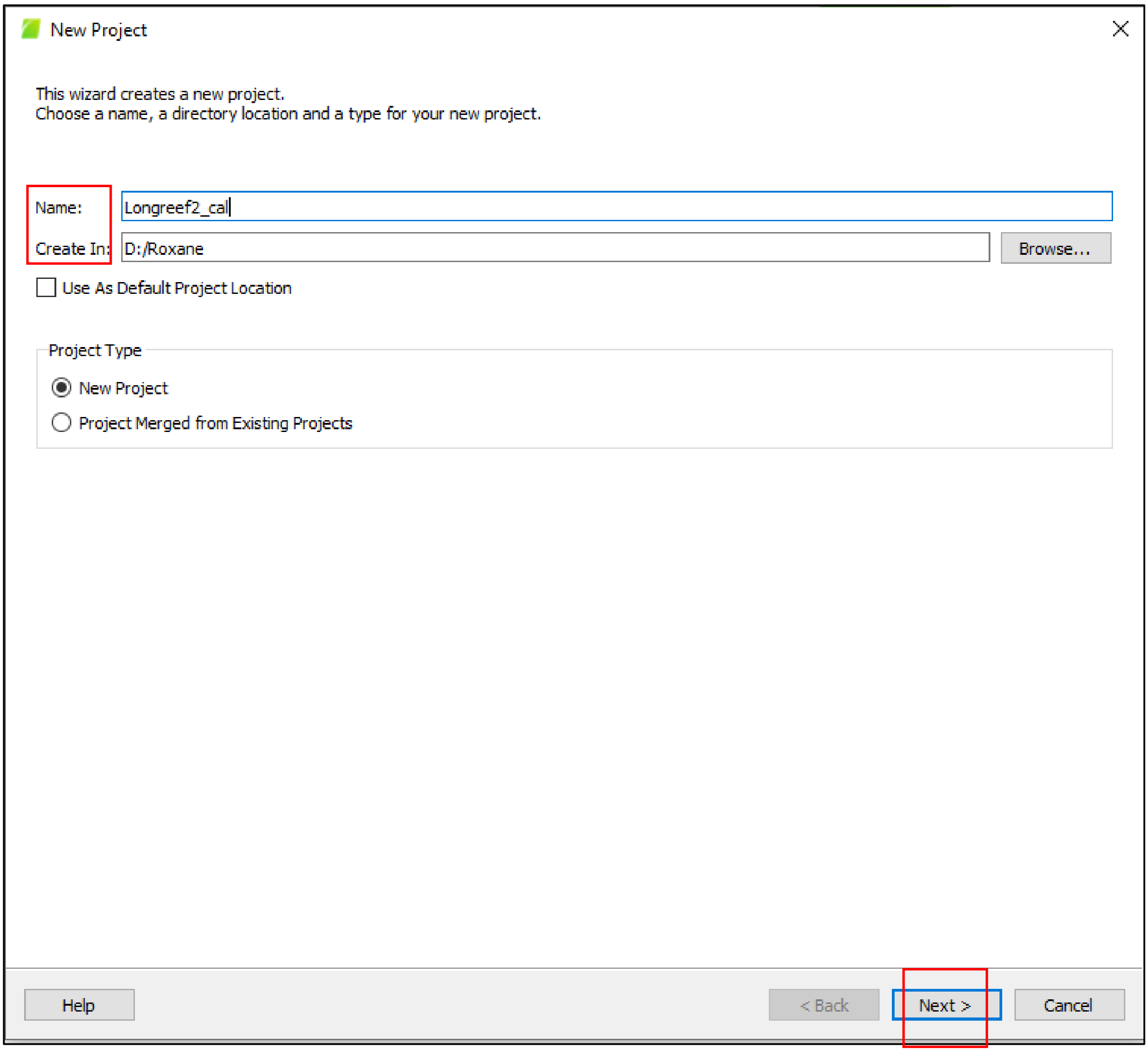

Figure C-1 Setting up a project

C3 Selecting imagery for processing

Open the folder in your PC with the images from the transects flights (for the orthomosaic) and drag and drop all files into Pix4D (Figure C-2). Once completed select “Next”.

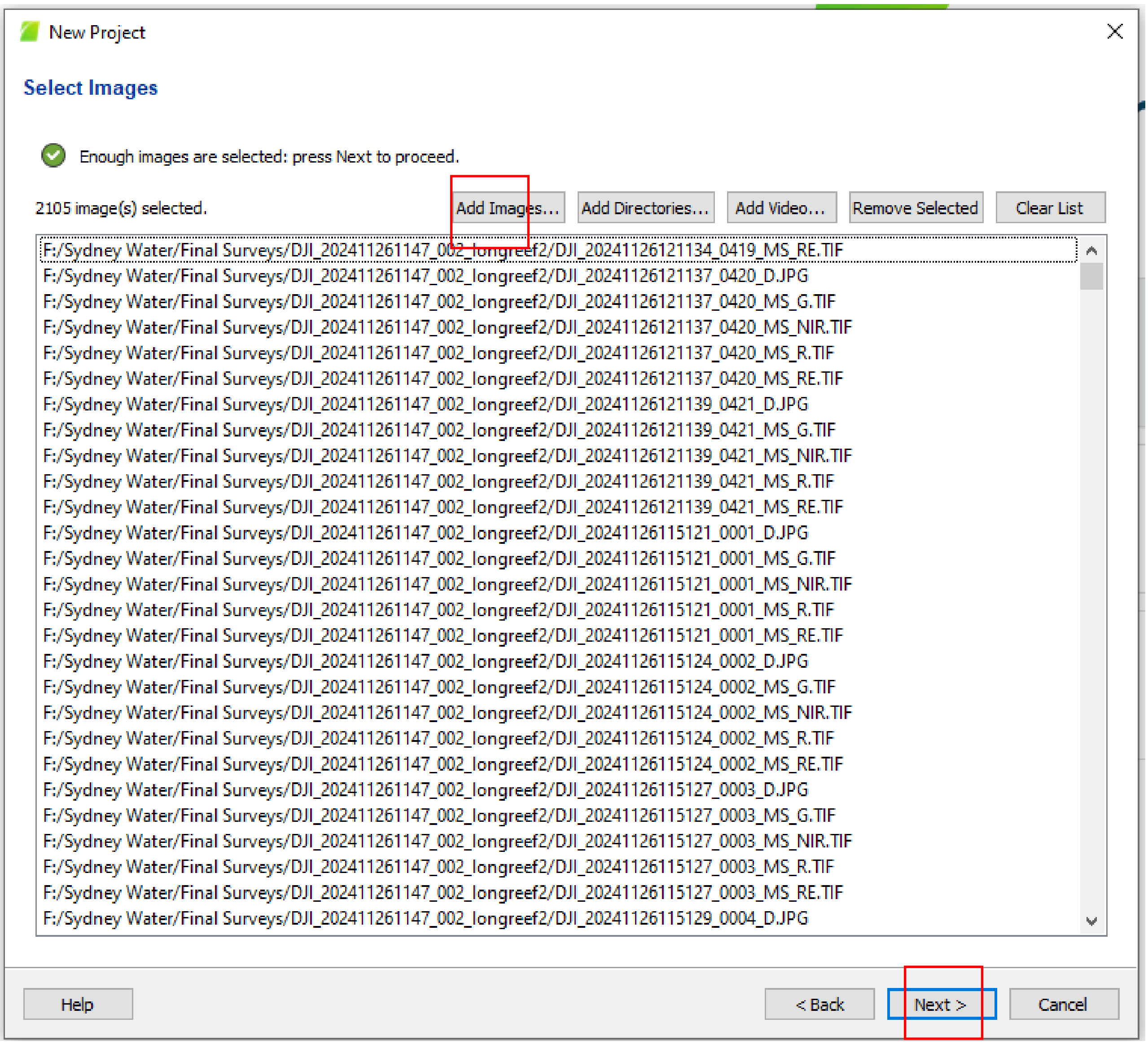

Figure C-2 Image selection

C4 Assigning image properties

Pix4D will automatically read the EXIF metadata from the imagery, assign a coordinate system, and read the camera model. Verify this is correct (Figure C-3) and select "Next".

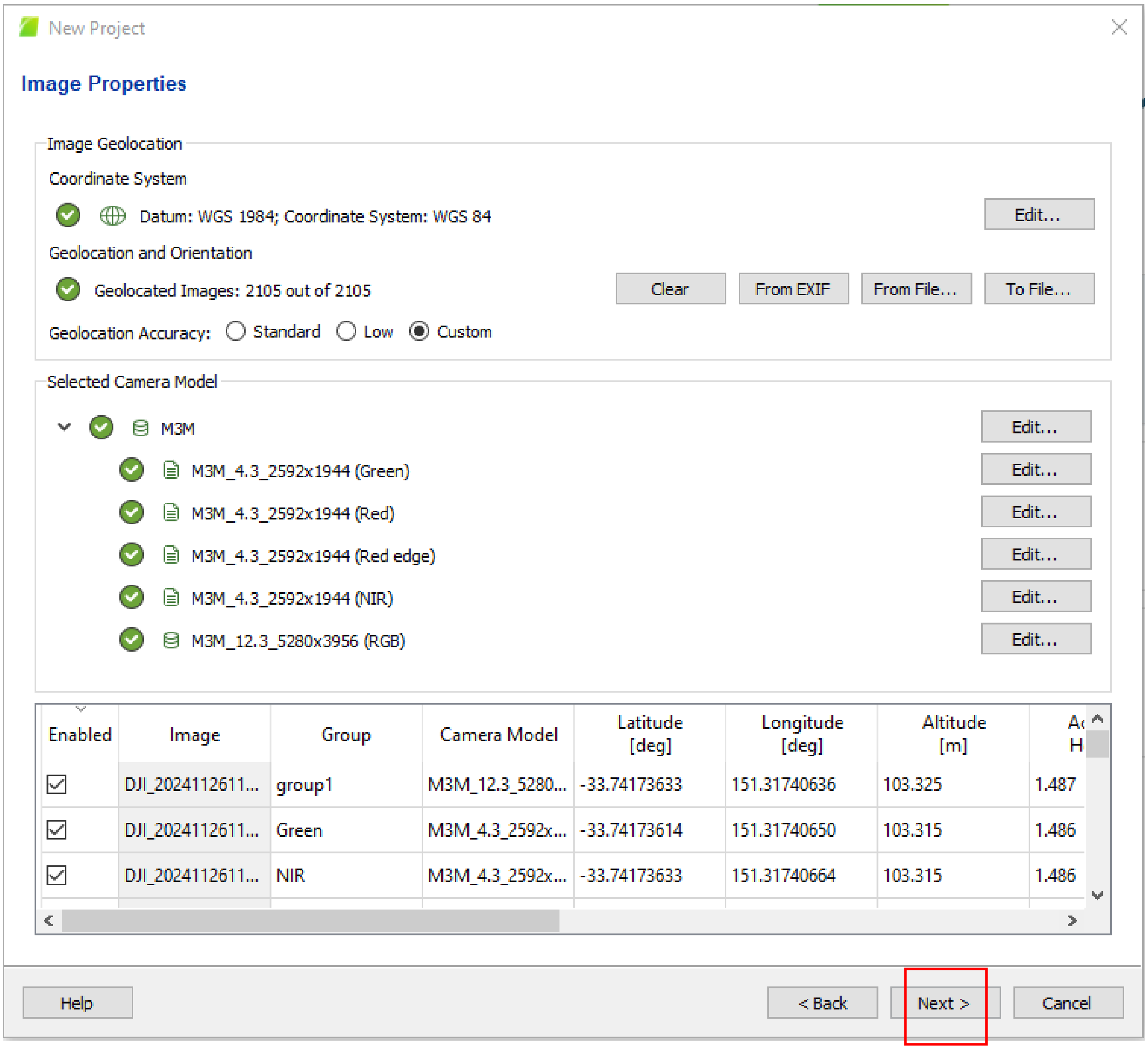

Figure C-3 Image properties

C5 Assigning a coordinate system.

Coordinate system will be automatically assigned. Verify this is correct (Figure C-4) and select "Next".

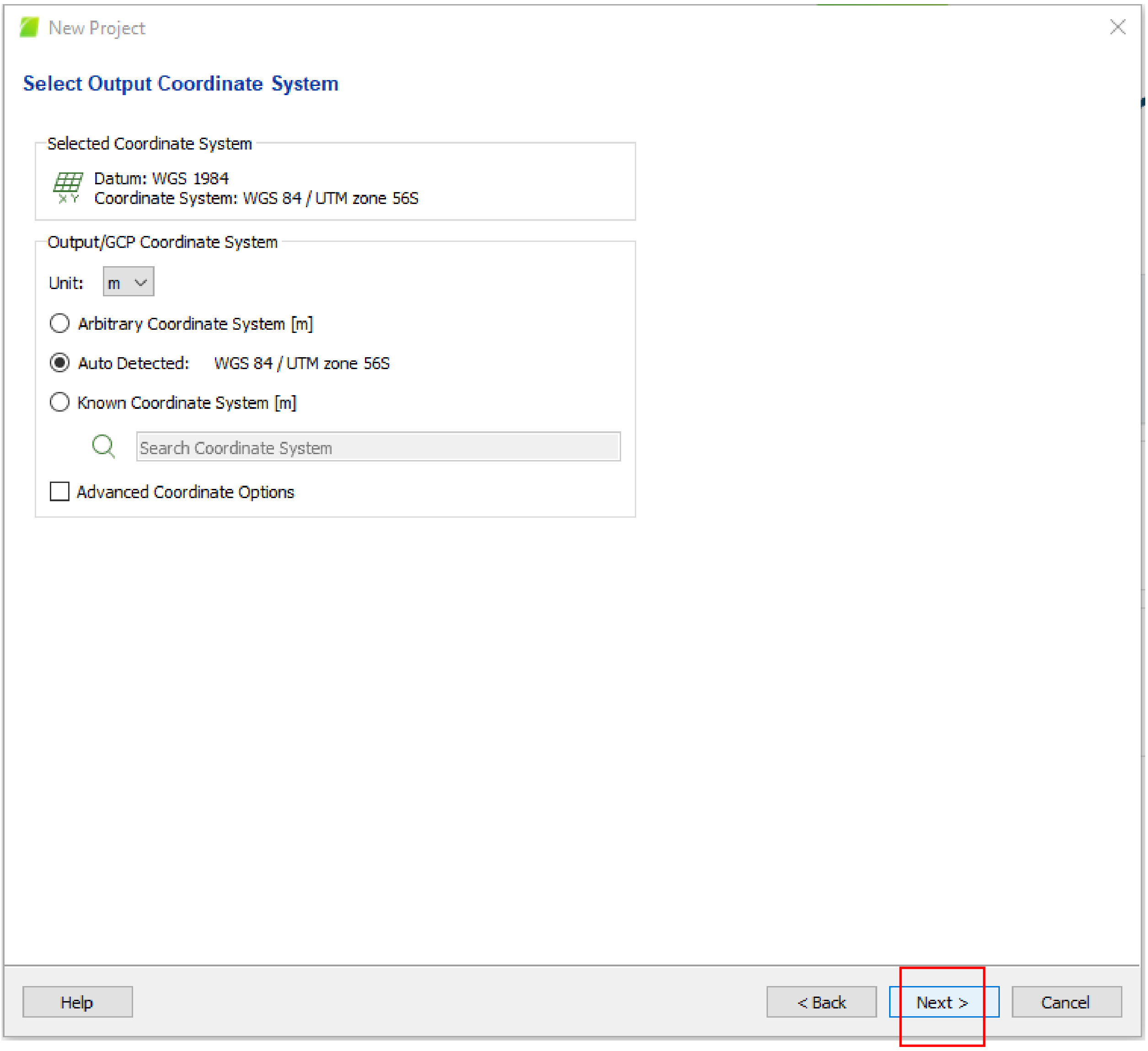

Figure C-4 Processing coordinate system

C6 Assign processing template

Next (Figure C-5):

- Select "Ag Multispectral"
- Untick "Start Processing Now"
- Select "Finish"

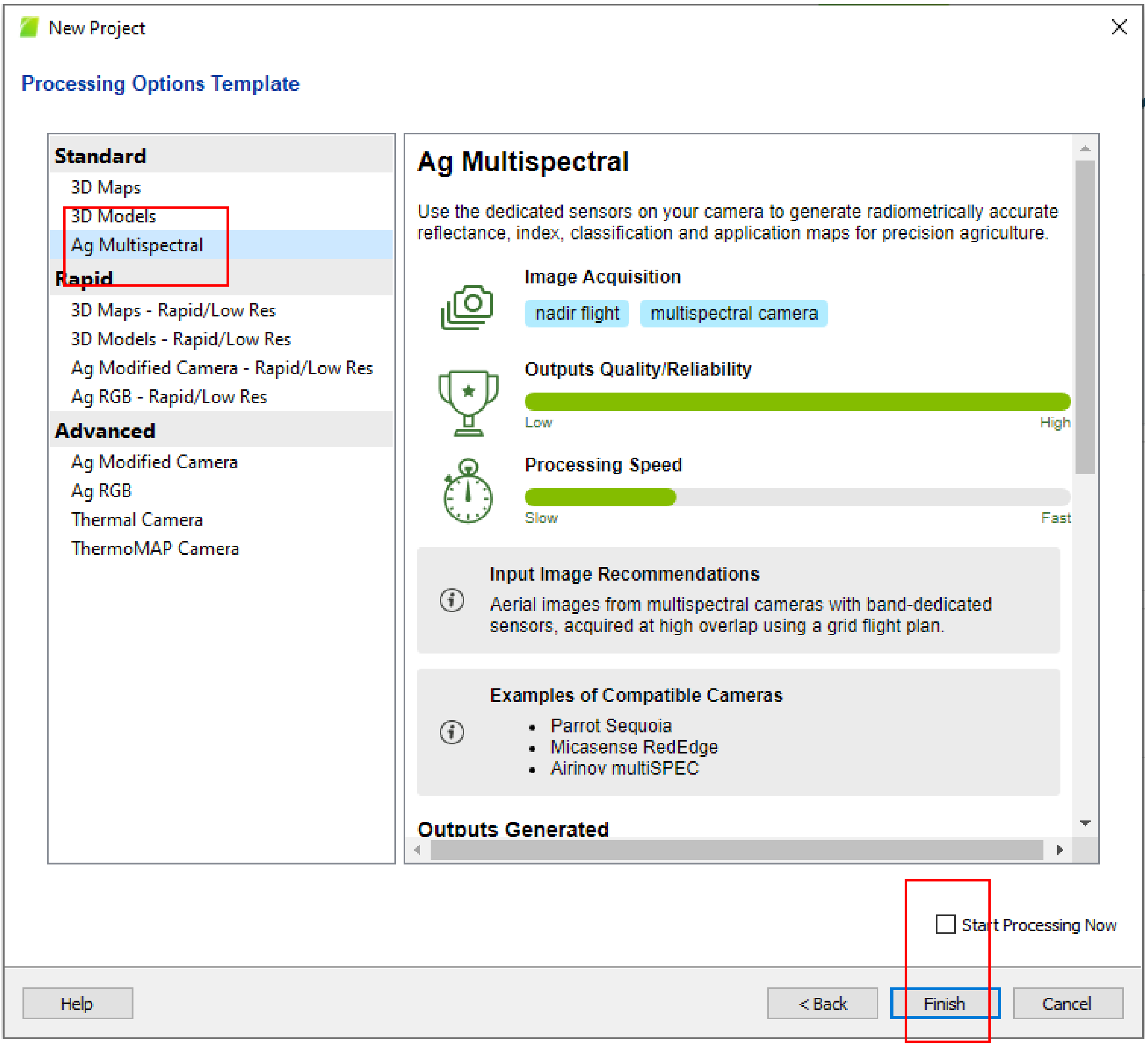

Figure C-5 Assign processing template

C7 Program processing options

On the next screen, select "Processing Options" in the bottom left corner (Figure C-6). A new window will appear (Figure C-7). On this new window, select the "DSM and Orthomosaic" tab and select "Raster DSM". Also select "Merge Tiles", "Orthomosaic", and "Merge Tiles".

Next, select the "Additional Outputs" tab and select the "Raster DTM" and "Merge Tiles" boxes (Figure C-8).

Finally, select the "Index Calculator" tab and calibrate each Green, Red, Red edge and NIR sensor (Figure C-9). To do this for each band, select "Calibrate" and browse to the image location of the sensor panel taken before the flight, ensuring you choose "_G" for Green, "_R" for red etc. (Figure C-10). Draw the reflectance panel surface by pressing the left mouse button, and finalise by pressing the right mouse button. Enter the Reflectance factor according to the table taken from Specifications | Sentera Calibrated Reflectance Panel User Guide. For this project the Sentera Reflectance Panel for 6X was used with the Mavic 3M drone (Figure C-11), which has the specific reflectance values listed in Figure C-12.

Once, the calibration values have been set, select the "Reflectance Map" and "Merge Tiles" options (Figure C-13), and add the additional Indices "Red_edge_red_edge", "group1_grayscale" and "ndvi" (see also Figure C-13). Finally, select "OK".

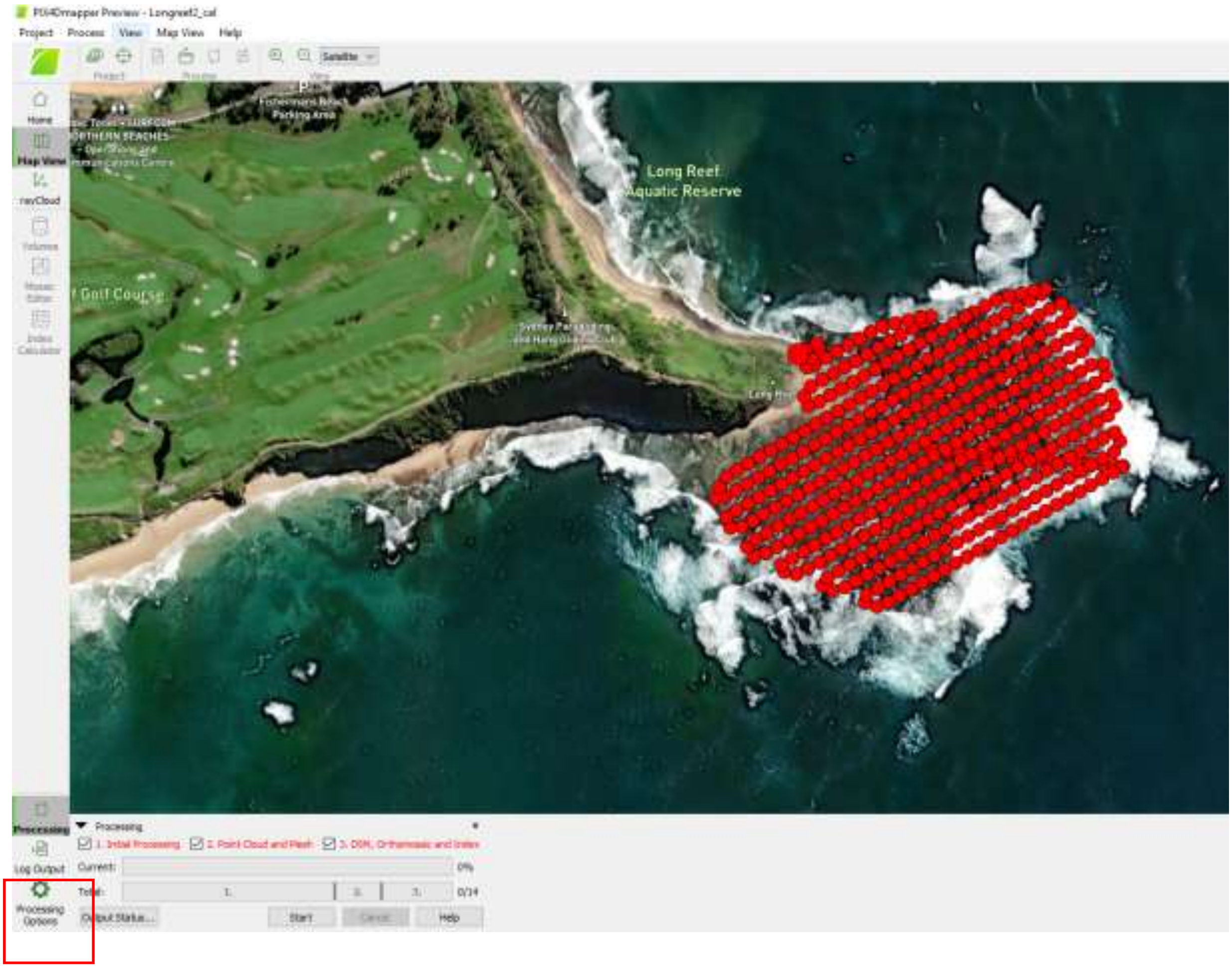

Figure C-6 Select processing options

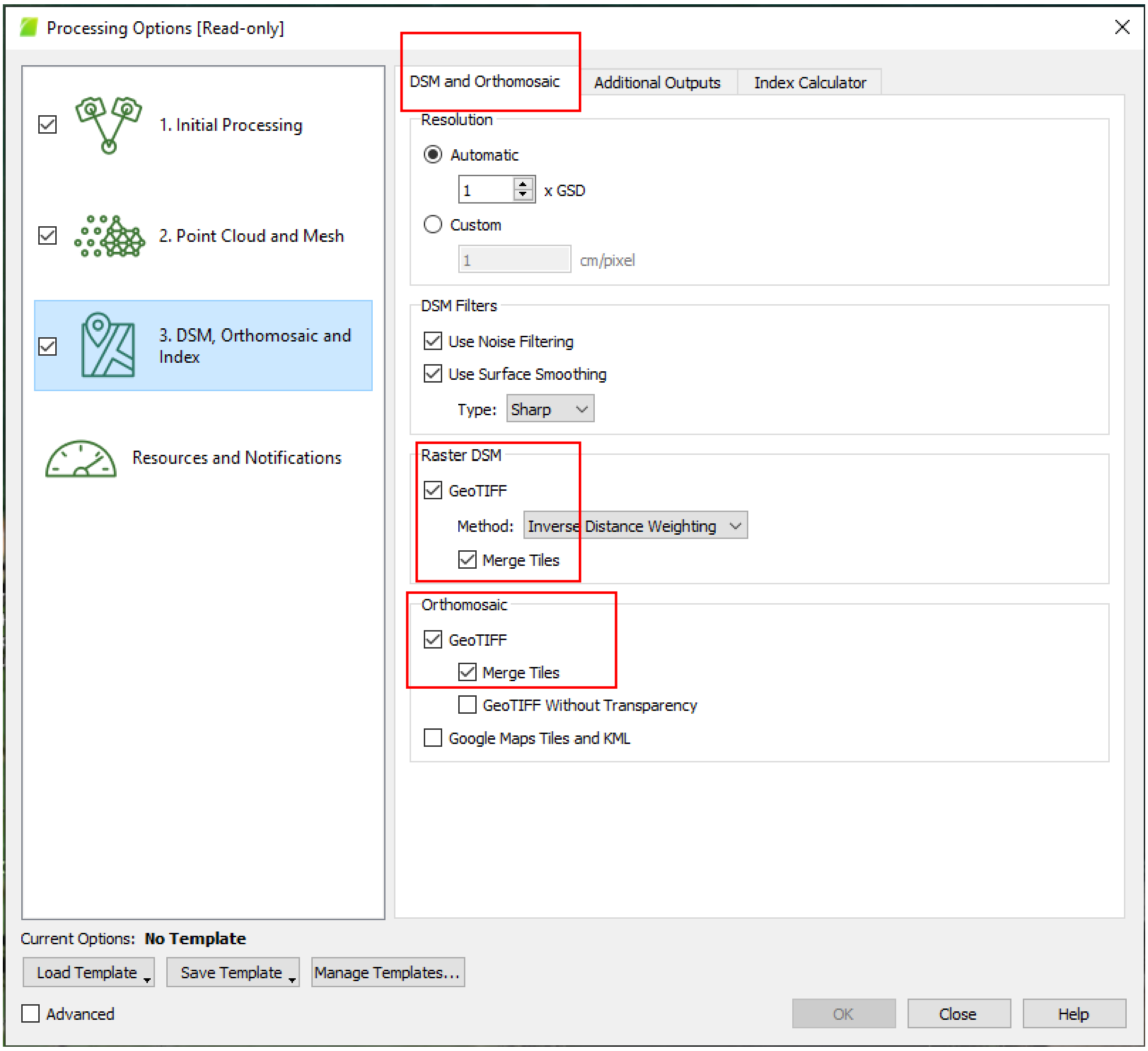

Figure C-7 Program processing options (DSM and Orthomosaic)

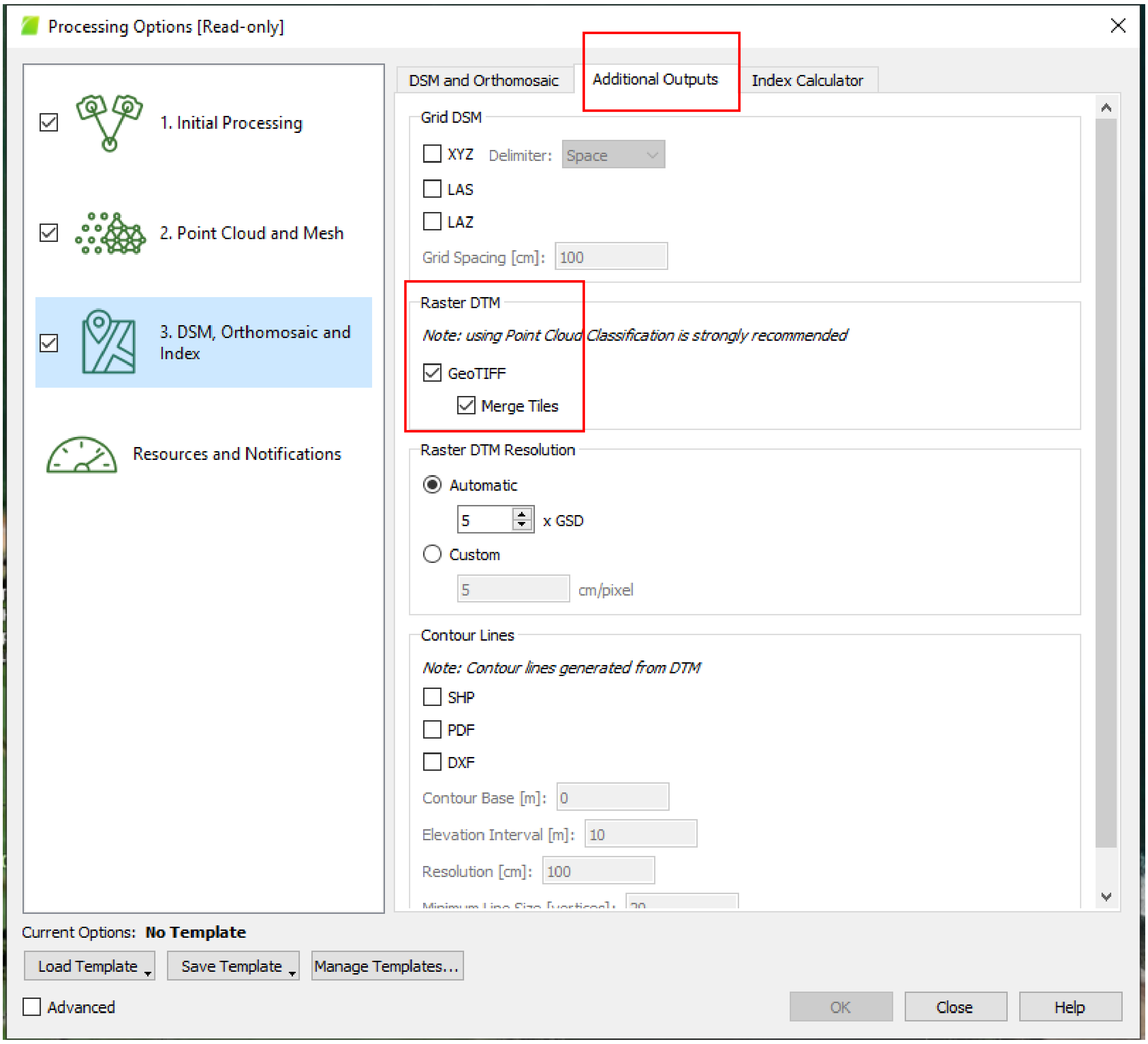

Figure C-8 Program processing options (Additional Outputs)

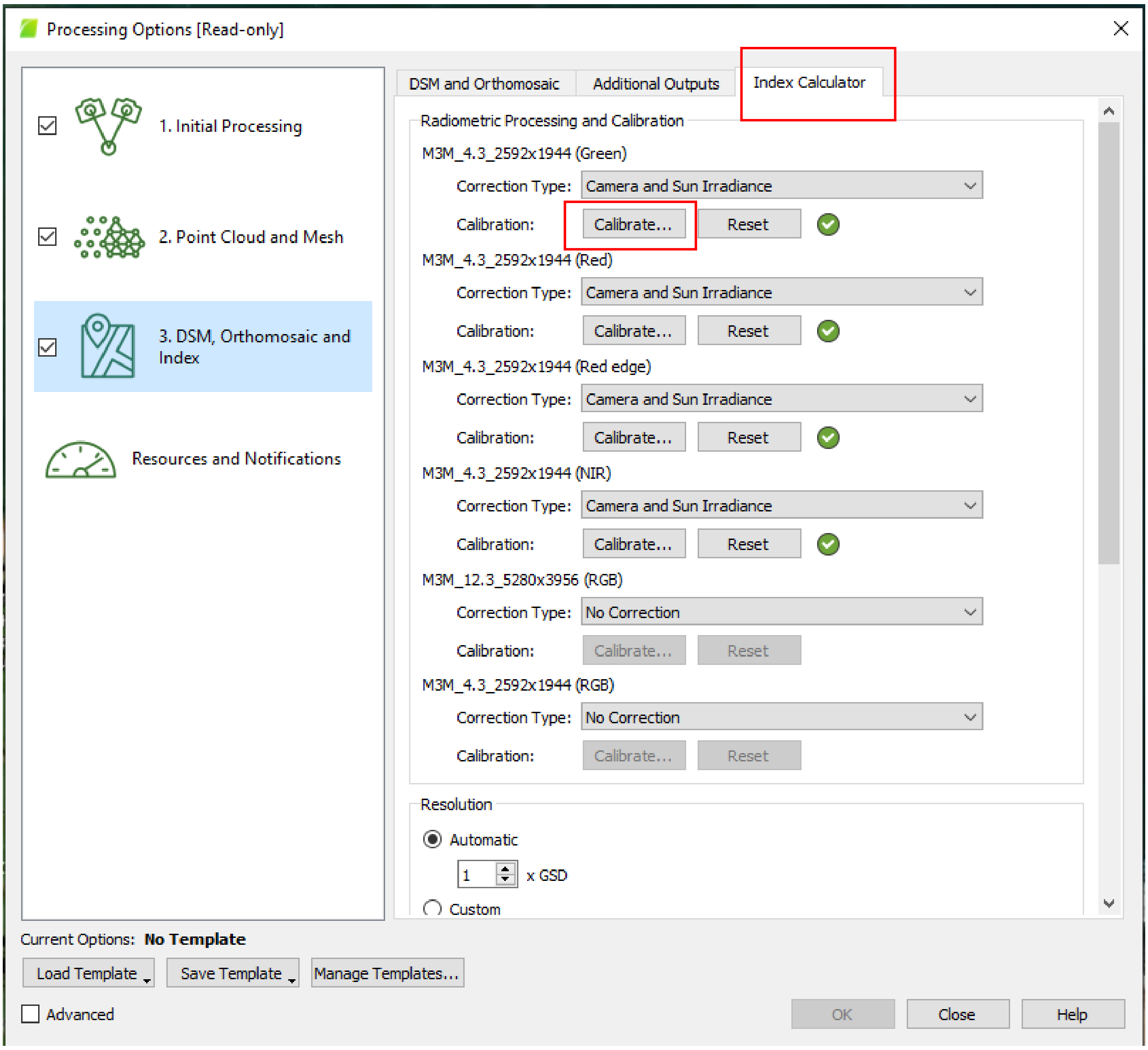

Figure C-9 Program processing options (Index Calculator)

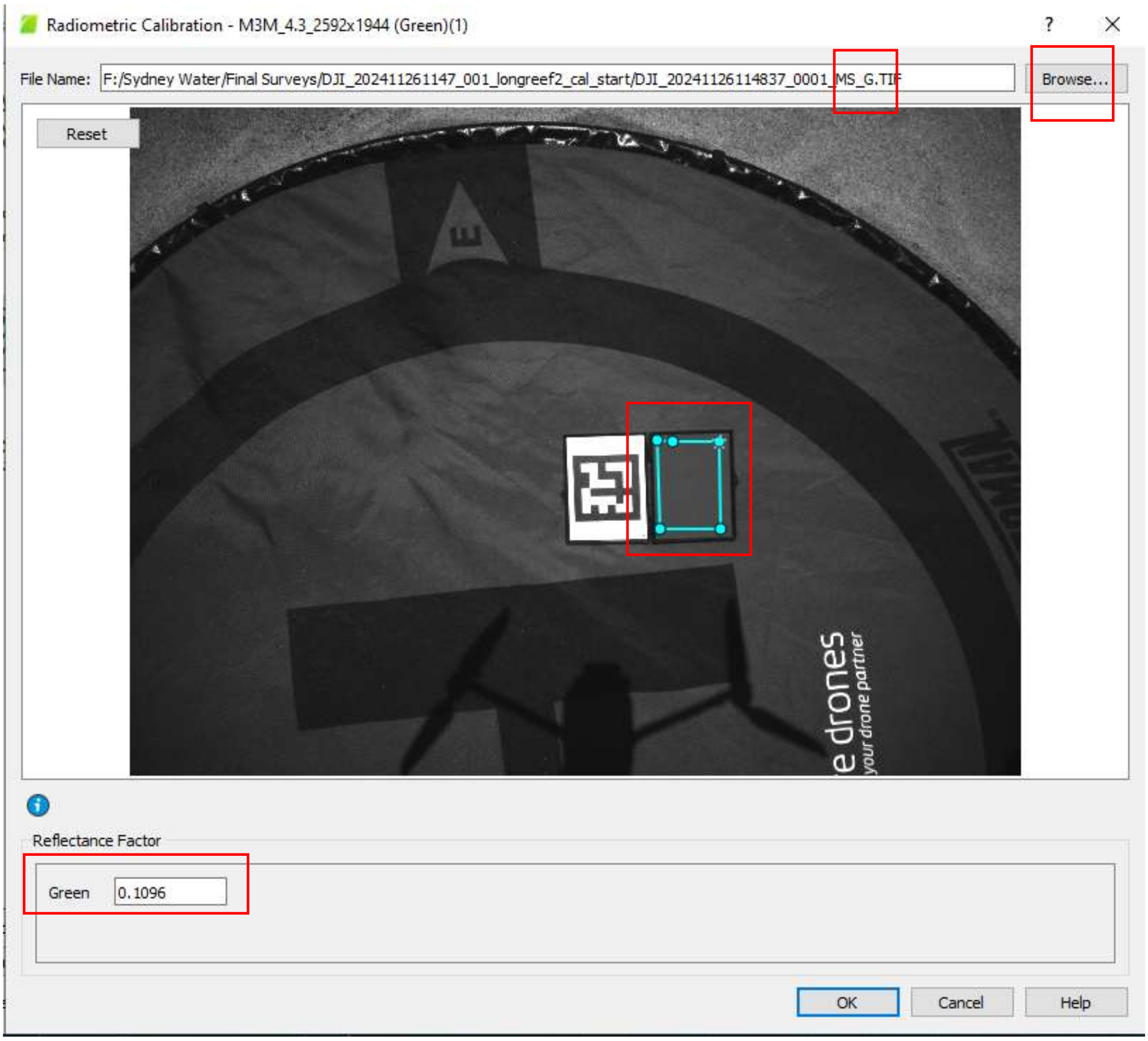

Figure C-10 Selecting the reflectance panel calibration imagery and assigning the reflectance factor

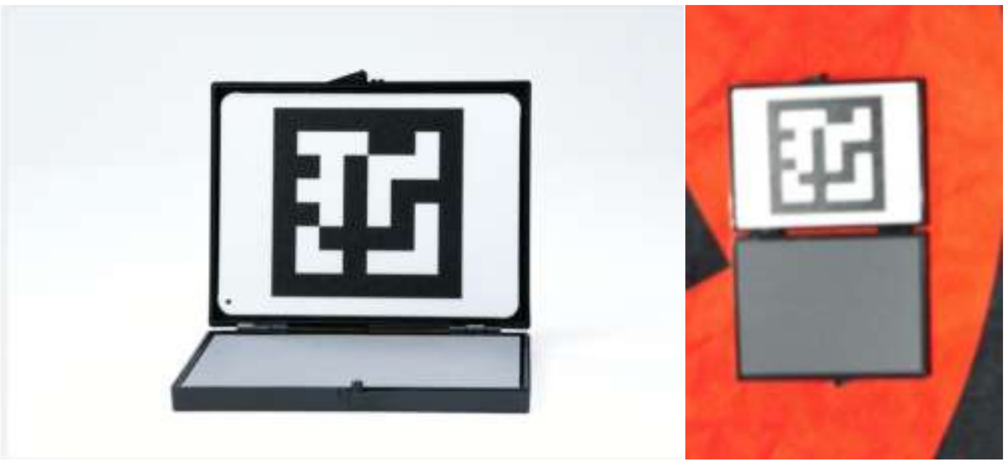

Figure C-11 Sentera Reflectance Panel

Coefficients

Channel	Value
Blue (475nm)	0.1116
Green (550nm)	0.1099
Green (560nm)	0.1096
Red (650nm)	0.1081
Red (670nm)	0.1079
Red Edge (715nm)	0.1071
Red Edge (730nm)	0.1069
Near Infrared (840nm)	0.1050
Near Infrared (860nm)	0.1049

Figure C-12 Sentera Reflectance Panel specific reflectance values

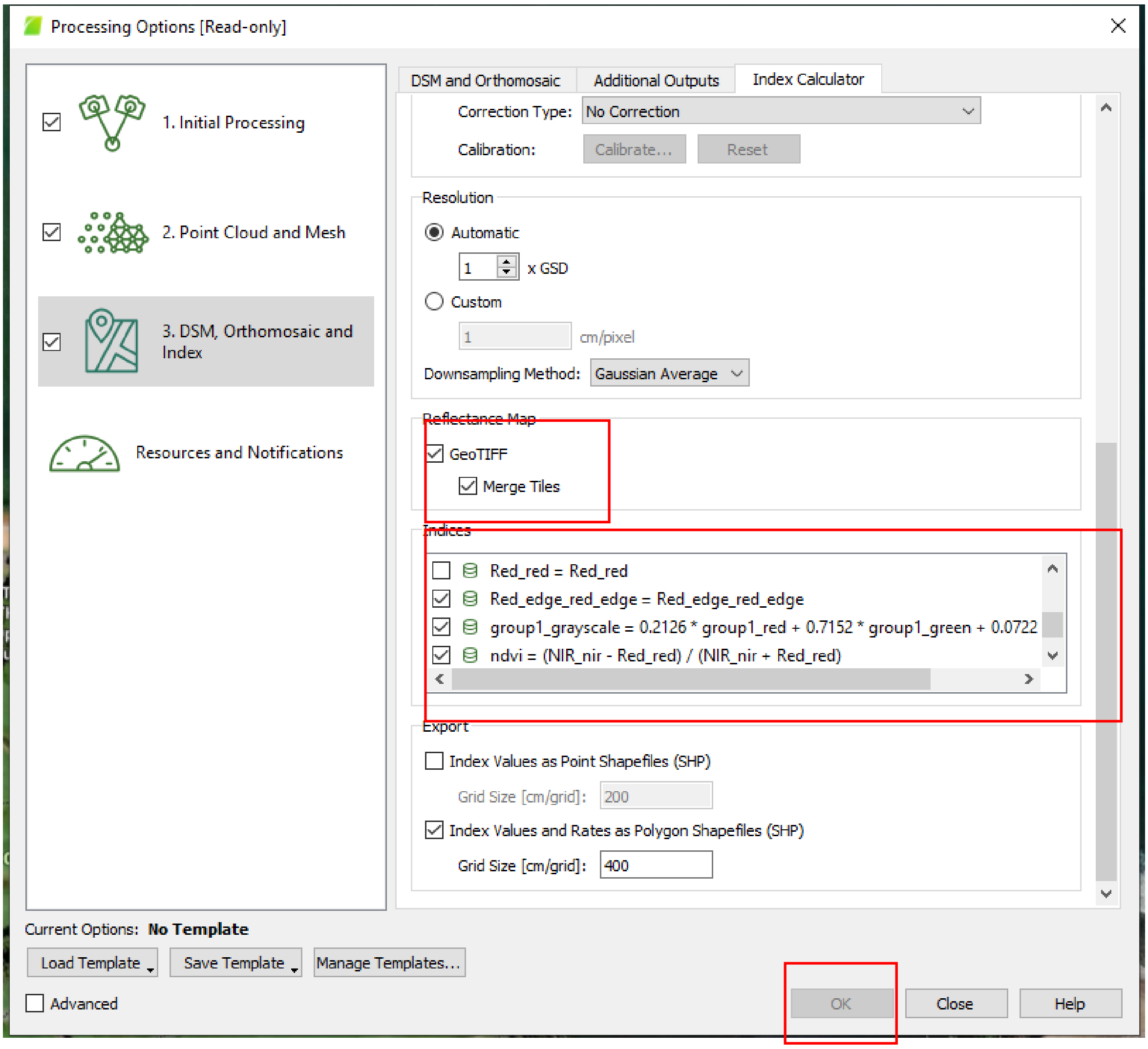

Figure C-13 Additional Index Calculator options

C8 Start image processing

On the “Map View” screen select “Start” in the bottom left (Figure C-14). Image processing will begin with the first stage (initial processing) followed by the second (Point cloud and mesh) and third (DSM, orthomosaic and index) stages. A status bar will indicate the process. Image processing time will depend on the number of images included in the analysis and could take in the order of hours. Once completed, processed data will be saved to the file locations specified at the start of the image processing procedure.

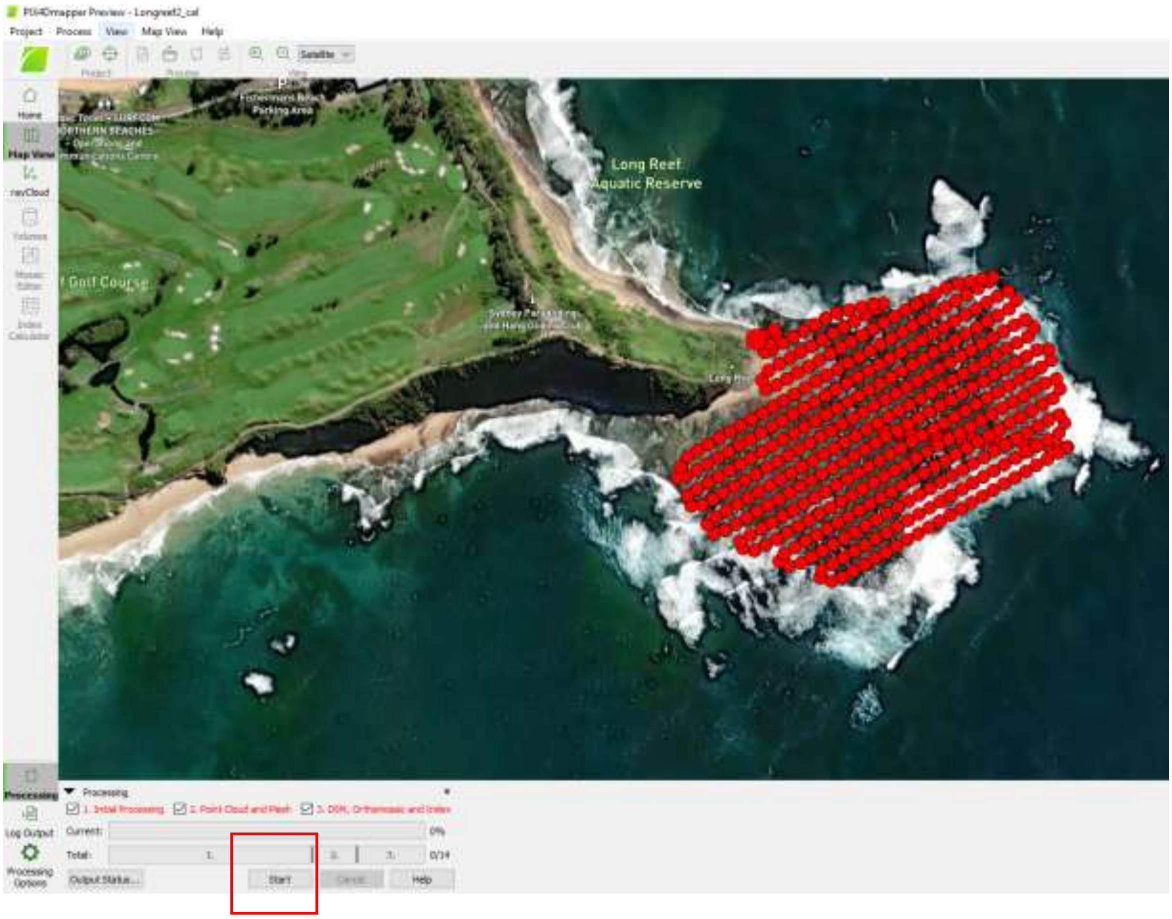

Figure C-14 Start image processing

Appendix D Image processing documentation

D1 Overview

The following section outlines the image processing methodology. Information provided here is supplemented by source code and documentation which has been made available on GitHub (github.com/unsw-wrl/quadrat-coverage).

The methodology in Drummond & Howe (2018) included the following steps:

- Image collection and processing
- NDVI calculation
- Clipping
- Thresholding
- Quadrat generation
- Zonal statistics

The workflow used in the current study follows the same steps, but a new QGIS extension with a graphical user interface was developed to make the analysis more user friendly (Figure D-).

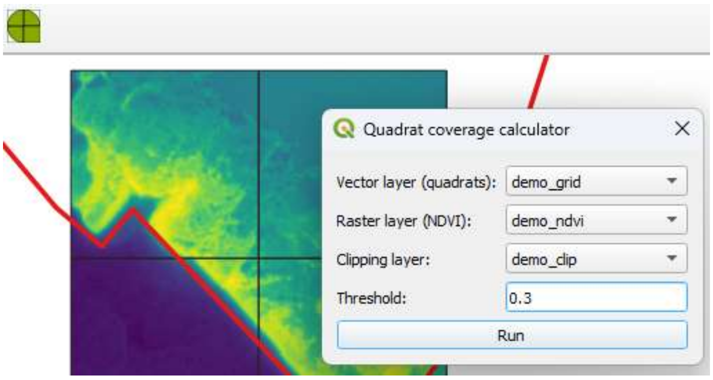

Figure D-1 Screenshot of new QGIS quadrat coverage calculator extension

The new workflow also includes a different zonal statistics software package. Previously the ‘rasterstats’ (Perry, 2017) python package was used, but since then a faster and more robust package ‘exactextract’ (Baston, 2025) has become available. The selection of a zonal statistics package is important. Many packages produce unexpected results in edge cases, for example when quadrats are only partially covered by a raster (Figure D-2).

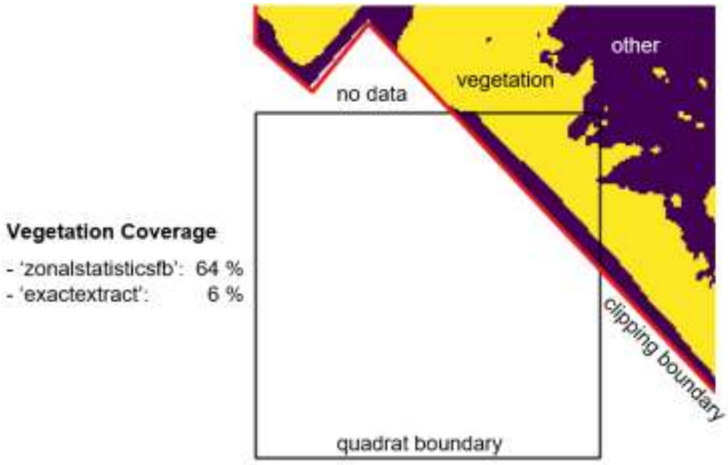

Figure D-2 Quadrat with partial raster coverage

In the example shown, the QGIS built-in zonal statistics calculator 'zonalstatisticsfb' gives a vegetation coverage of 64% for the quadrat. This result is misleading because the region outside the clipping boundary is ignored instead of counting towards the unvegetated fraction of the total quadrat. The 64% figure does not represent the total quadrat and therefore cannot be used when aggregating results over multiple quadrats. In contrast, the 'exactextract' package allows the 'no data' region of the quadrat to be included in the calculation, giving a correct vegetation coverage of 6%.

D2 Image collection

Add RGB and NDVI orthomosaic images to the QGIS map canvas (Figure D-3).

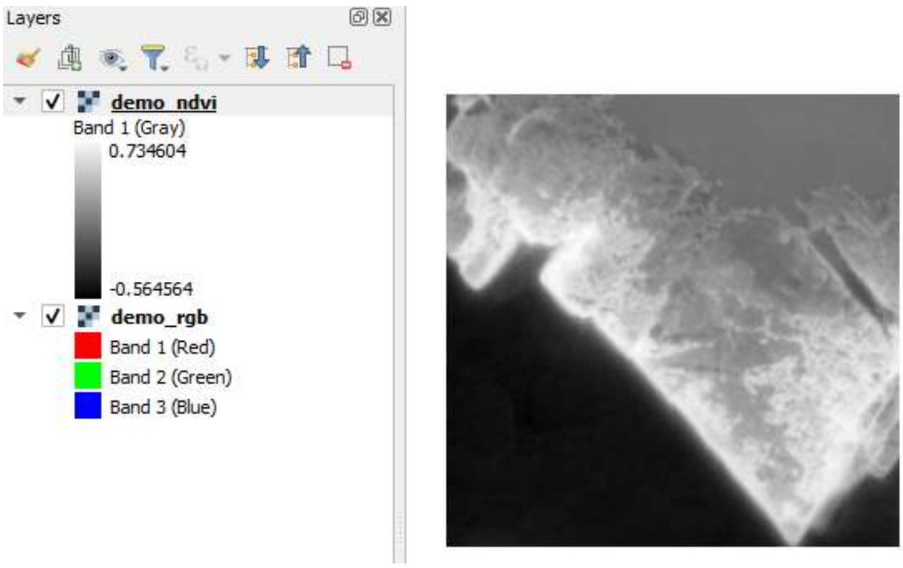

Figure D-3 NDVI image in QGIS map canvas

D3 Clipping

Import or create a new vector layer to clip unwanted water and vegetation regions including trees, shrubs, and grass (Figure D-4).

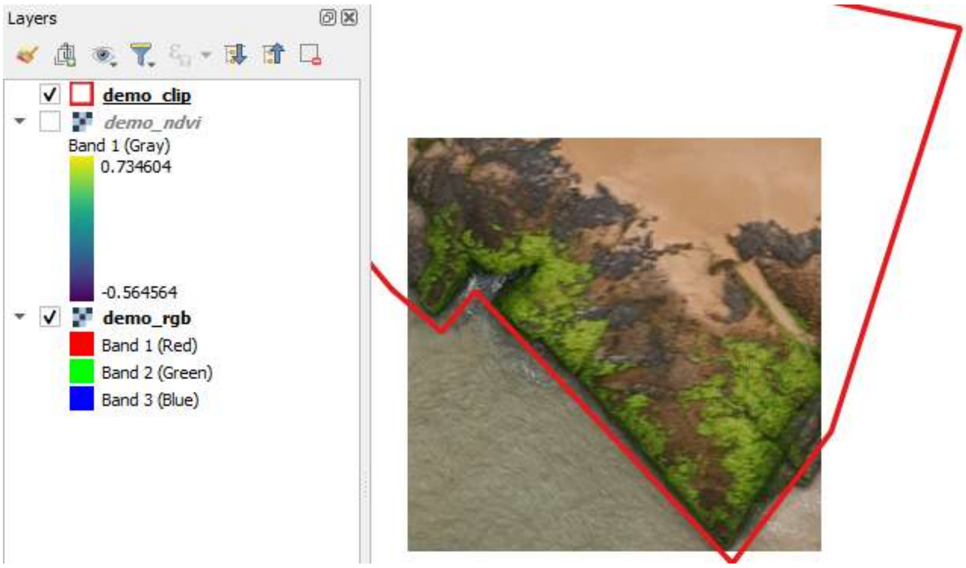

Figure D-4 Creating clipping boundary

D4 Thresholding

Change the symbology settings on the NDVI raster (Figure D-5) to choose an appropriate threshold value.

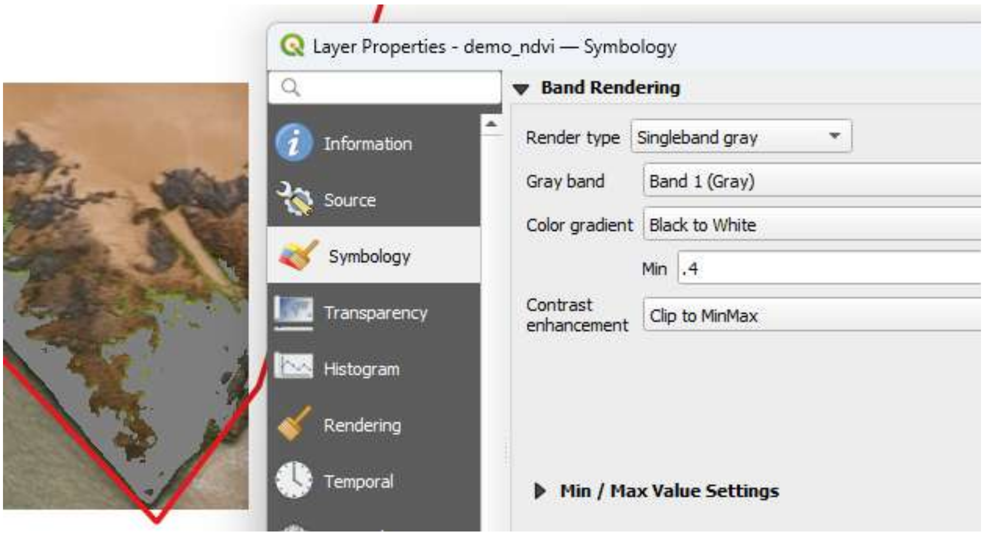

Figure D-5 Symbology dialog

With the contrast enhancement set as 'Clip to MinMax', the values below the NDVI threshold become transparent, revealing the RGB layer underneath (Figure D-6).

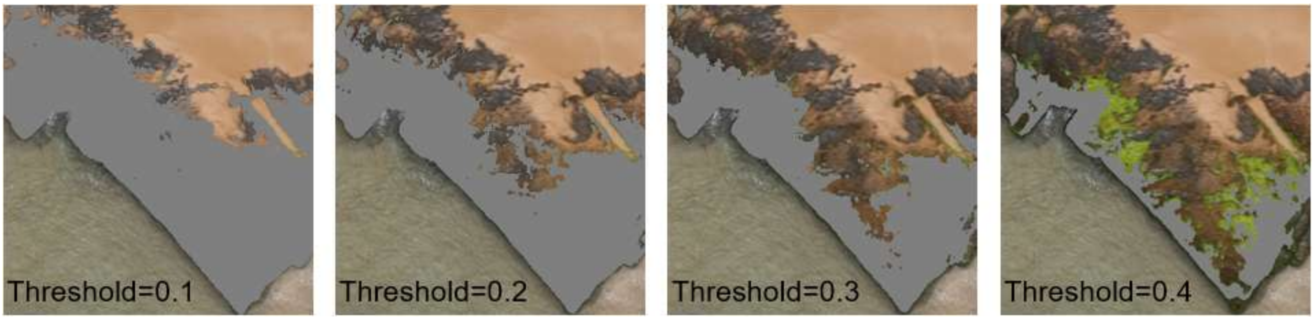

Figure D-6 Comparison of different threshold values

D5 Quadrat generation

Select 'Vector'-> 'Research Tools'-> 'Create Grid', choose 'Rectangle (Polygon)' as the grid type, and set the desired horizontal and vertical spacing (Figure D-7).

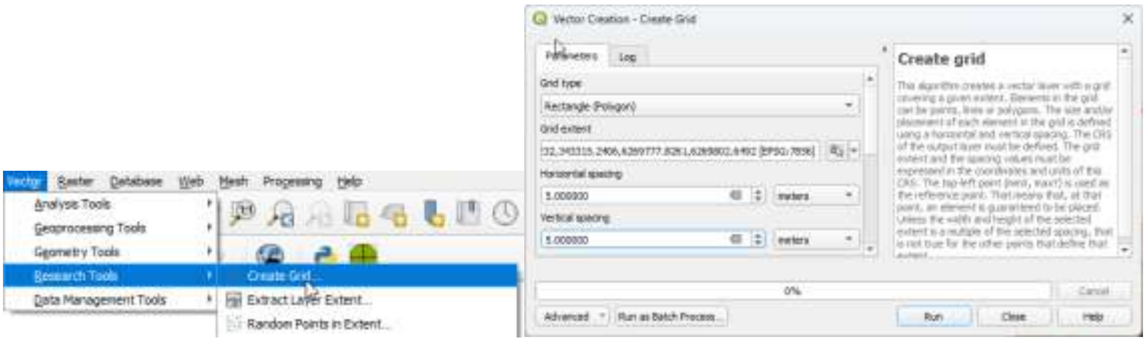

Figure D-7 Grid generation

D6 Zonal statistics

Open the ‘Quadrat coverage’ dialog (see https://github.com/unsw-wrl/quadrat-coverage for installation instructions) and select input values (Figure D-8).

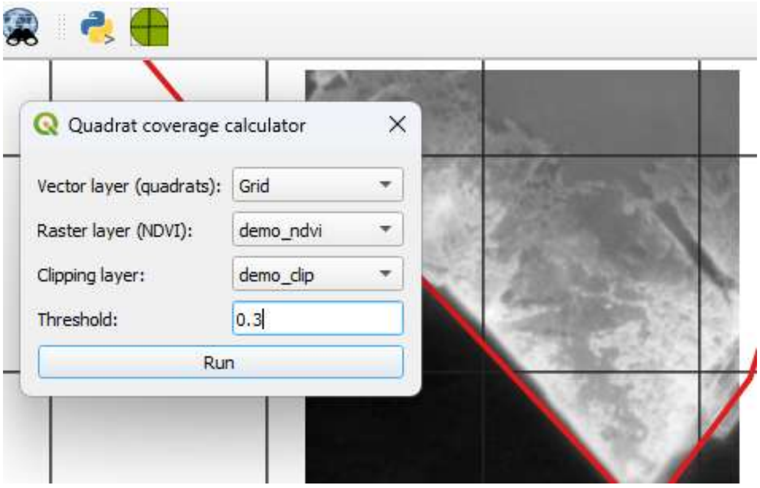

Figure D-8 Quadrat coverage dialog

Turn on labels and change the symbology on the newly created ‘Quadrat Coverage’ layer as required (Figure D-).

Figure D-9 Percent coverage values