ENVIRONMENTAL SENSING AT THE UNIVERSITY OF SOUTHAMPTON

the River Restoration Centre
*Working to restore and enhance our rivers*

# UPDATES TO THE PRAGMO GUIDANCE

## UNCREWED AERIAL VEHICLES (UAVS) FOR RIVER RESTORATION MONITORING

Dr Chris Tomsett[1,2], Guy Daniel[1], Kathryn Vaughan[1], Edward Fleming[7], Jamie Parton[3], Dr Sam Austin[4], Dr Marc Naura[4], Peter Morgan[1,2], Alex Deacon[5], Mike Blackmore[5], Prof Chris Hill[1,3], Prof Julian Leyland[1,2]

[1]School of Geography and Environmental Science, University of Southampton
[2]Environmental Sensing @ Southampton
[3]School of Engineering, University of Southampton,
[4]Geodata Institute
[5]River Restoration Centre
[6]Wessex Rivers Trust
[7]Fishtek

# Contents

# 1 Executive Summary

River restoration practice in the United Kingdom is increasingly shaped by regulatory drivers, biodiversity targets, and the need to enhance resilience to hydrological and climatic change. Within this context, the Practical River Restoration Appraisal Guidance for Monitoring Options (PRAGMO), developed by the River Restoration Centre, provides a structured framework for defining monitoring objectives, selecting indicators, and evaluating restoration outcomes. However, the effective implementation of PRAGMO is often constrained by limitations in data acquisition, including the difficulty of capturing spatially continuous information across river corridors, restricted site access, and challenges in integrating geomorphological, hydrological, and ecological observations.

Uncrewed Aerial Vehicles (UAVs) provide a step change in the way such data can be acquired and analysed. They enable the collection of high-resolution, spatially continuous datasets across entire river reaches, bridging the gap between fine-scale field observations and system-scale understanding. Their repeatability allows consistent data acquisition through time, supporting robust multi-temporal analysis and the quantitative assessment of change. As such, UAVs do not replace established monitoring approaches, but enhance them by providing spatial context, improving efficiency, and enabling more integrated analysis.

Within the PRAGMO framework, UAVs are best understood as a method of data acquisition and analysis that supports the measurement of indicators, rather than as an objective in their own right. Their greatest value lies in enabling the translation of restoration objectives into measurable, spatially explicit variables. UAV-derived datasets support baseline characterisation by providing detailed representations of channel morphology, vegetation structure, and floodplain connectivity. During monitoring, they allow indicators to be quantified across entire reaches, capturing spatial heterogeneity that is often missed by point-based surveys. Through repeat surveys, they support the evaluation of system response, enabling restoration outcomes to be assessed in terms of magnitude, direction, and spatial pattern.

UAV-based monitoring is particularly effective in four domains central to river restoration: (i) topographic and morphological characterisation, where terrain models enable the quantification of channel form and complexity; (ii) change detection and sediment dynamics, where multi-temporal datasets allow erosion and deposition to be measured directly; (iii) vegetation structure and habitat mapping, where spectral and three-dimensional data support the assessment of riparian condition; and (iv) hydrological and hydraulic proxies, where image-based approaches provide insight into flow dynamics, connectivity, and thermal regimes. Together, these capabilities enable a shift from descriptive to quantitative, process-based monitoring.

Despite these advantages, UAV-based approaches are subject to important constraints. Data quality is sensitive to environmental conditions, including vegetation cover, lighting, and water clarity. Photogrammetric methods are limited in densely vegetated environments, while bathymetric and hydrodynamic applications are dependent on suitable surface conditions. UAV surveys also generate large datasets that require appropriate processing workflows and technical expertise. In addition, operations must comply with Civil Aviation Authority regulations, and uncertainty, particularly in change detection, must be explicitly managed through robust georeferencing and standardised protocols.

To maximise their value within PRAGMO, UAV deployment should be objective-led and proportionate to monitoring needs. Surveys should be designed to ensure repeatability, supported by appropriate georeferencing strategies (e.g. RTK or PPK with validation), and integrated with targeted field-based observations. Emphasis should be placed on deriving decision-relevant metrics rather than maximising data volume. Where applied in this way, UAVs enable more efficient, consistent, and analytically robust monitoring.

Looking forward, UAVs are likely to play an increasingly central role in river restoration, particularly as they become integrated with digital workflows, automated analysis, and emerging decision-support frameworks. By embedding UAV-based approaches within PRAGMO, practitioners can move towards more quantitative, spatially explicit, and adaptive monitoring, ultimately supporting more effective restoration design and management across UK river systems.

# 2 Where UAVs Fit Within PRAGMO

## 2.1 Positioning UAVs within the PRAGMO Framework

PRAGMO provides a structured approach to monitoring river restoration through the definition of objectives, selection of indicators, and application of proportionate methods. Central to this framework is the principle that monitoring should be fit-for-purpose, cost-effective, and directly linked to decision-making, rather than driven by data availability or technological capability.

Within this structure, UAVs are most appropriately understood as a means of acquiring and analysing spatial data, rather than as a monitoring objective or indicator in their own right. Their role is to support the measurement of indicators by providing datasets that are spatially continuous, repeatable, and scalable across river reaches and floodplains.

This positioning is consistent with the River Restoration Centre’s broader strategic emphasis on improving the quality, consistency, and accessibility of monitoring data, and on enabling practitioners to move from descriptive assessments towards more quantitative and comparable evaluation of restoration outcomes. UAVs contribute to this aim by allowing a range of PRAGMO-relevant variables, particularly those relating to geomorphology, vegetation structure, and hydrological connectivity, to be measured in a consistent and reproducible manner. Conceptually, UAVs occupy the interface between methods and evidence, enabling the translation of restoration objectives into measurable, spatially continuous variables. Their role within the PRAGMO workflow is summarised in Table 2-1.

*Table 2-1: Conceptual positioning of UAVs within the PRAGMO workflow.*

| PRAGMO Stage | Role of UAVs | Contribution to Monitoring |
|---|---|---|
| Objective definition | Baseline mapping and spatial context | Supports identification of system condition and variability |
| Indicator selection | Identification of measurable spatial variables | Enables translation of objectives into quantifiable metrics |
| Data acquisition | High-resolution spatial data collection | Provides continuous datasets across river corridors |
| Analysis and evaluation | Multi-temporal comparison and spatial analysis | Supports quantification of change and system response |
| Adaptive management | Evidence provision | Informs refinement of interventions and monitoring design |

## 2.2 Supporting Objective Definition and Baseline Characterisation

PRAGMO places strong emphasis on the definition of clear and measurable objectives at the outset of a project. In practice, this requires an understanding of baseline conditions that extends beyond site descriptions to include the spatial organisation of channel and floodplain processes. UAV-derived datasets provide a practical means of establishing this baseline. High-resolution orthomosaics allow for the mapping of channel planform, geomorphic features, and anthropogenic modifications, while digital elevation models derived from photogrammetry or LiDAR provide a continuous representation of terrain. These datasets can be used to characterise channel width variability, identify zones of erosion or deposition, and delineate riparian vegetation patterns across entire reaches. Importantly, this spatial perspective enables practitioners to move beyond reliance on isolated survey locations, supporting the identification of representative monitoring sites and informing the selection of appropriate indicators. In this sense, UAVs contribute not only to data collection, but also to the design of monitoring programmes, ensuring that objectives are grounded in observable system behaviour.

## 2.3 Indicator Measurement and Data Acquisition

Once monitoring objectives and indicators have been defined, UAVs provide a flexible platform for acquiring the data required to support their measurement. In an existing workflow, this process is articulated through a sequence of stages including site reconnaissance, pre-flight preparation, flight execution, and data processing . When aligned with PRAGMO, this workflow can be interpreted as the operationalisation of indicator measurement. For geomorphological indicators, UAV-derived terrain models enable the quantification of channel form, cross-sectional geometry, and spatial variability in bed elevation. Orthomosaics support the identification of geomorphic units such as bars and riffles, as well as the mapping of anthropogenic features. For vegetation-related indicators, UAV imagery can be used to delineate riparian extent, assess structural characteristics, and derive indices indicative of vegetation condition. Hydrological indicators, while less directly measurable, can be supported through the mapping of water extent, identification of connectivity pathways, and, in some cases, estimation of surface velocity using image-based techniques.

A key advantage of UAV-based data acquisition is the ability to generate spatially continuous datasets, enabling indicators to be assessed across entire reaches rather than at discrete sampling points. This is particularly relevant in systems where heterogeneity is a defining characteristic, and where point-based measurements may not adequately capture spatial variability. The relationship between objectives, UAV-derived metrics, and PRAGMO components can be conceptualised as a progression from intent to evidence, in which UAVs act as the primary mechanism for data generation. This progression is summarised in Table 2-2.

*Table 2-2: Linking PRAGMO objectives to UAV-derived metrics and outputs*

| Monitoring Objective | UAV Role | Typical Outputs | Key Considerations |
|---|---|---|---|
| Channel morphology and form | Terrain mapping (SfM / LiDAR) | DEMs, cross-sections, geomorphic feature maps | Vegetation and water may obscure ground surface |
| Sediment dynamics and change | Multi-temporal comparison | Elevation change maps (DoDs), sediment budgets | Requires consistent surveys and error thresholds |
| Riparian vegetation and habitat | Image and structure mapping | Vegetation extent, canopy height, shading | Complements field-based ecological surveys |
| Hydrological connectivity | Extent and pathway mapping | Inundation maps, flow pathways | Dependent on survey timing and flow conditions |

This table illustrates that UAVs are not tied to a single indicator or monitoring objective, but instead provide a flexible platform capable of supporting multiple components of the PRAGMO framework. The selection of UAV methods should therefore be driven by the specific objectives of a given project, rather than by the availability of particular technologies.

## 2.4 UAVs Across the Restoration Lifecycle

The contribution of UAVs extends beyond individual monitoring tasks to encompass the entire lifecycle of river restoration projects (Table 2-3). Their ability to provide consistent, high-resolution data makes them particularly valuable for linking pre- and post-intervention conditions within a unified analytical framework.

*Table 2-3: The use of UAVs across the full restoration lifecycle.*

| Stage | UAV Contribution | Example Outputs |
|---|---|---|
| Pre-restoration | Baseline mapping and constraint identification | Orthomosaics, DEMs, habitat maps |
| Design | Quantification of morphology and hydraulics | Cross-sections, slope, roughness proxies |
| Implementation | Monitoring of construction and disturbance | Change detection maps |
| Post-restoration | Outcome evaluation and trajectory analysis | DoDs, vegetation recovery metrics |
| Long-term monitoring | Repeatable, cost-effective surveys | Time series datasets |

By maintaining consistency in data acquisition and processing, UAVs enable practitioners to develop longitudinal datasets that capture the evolution of restored systems. This is particularly important for understanding delayed responses and non-linear dynamics, which are common in fluvial environments.

## 2.5 Complementarity with Existing Monitoring Approaches

It is important to recognise that UAV-based monitoring should be integrated with, rather than replace, existing field-based methods. Techniques such as the River Habitat Survey provide valuable information on species composition, habitat quality, and localised conditions that cannot be fully captured through remote sensing.

The strength of UAVs lies in their ability to provide spatial context for these observations, allowing site-based measurements to be interpreted within the broader structure of the river corridor. When used in combination, UAV and field-based approaches offer a more comprehensive understanding of river systems, supporting both detailed ecological assessment and system-scale analysis.

## 2.6 Value Proposition within PRAGMO

Within the PRAGMO framework, UAVs function as a versatile and integrative monitoring tool, capable of supporting all stages of the monitoring cycle. Their primary value lies in enabling the translation of restoration objectives into measurable, spatially explicit metrics, thereby strengthening the link between monitoring and decision-making. By embedding UAV-based approaches within PRAGMO, practitioners can enhance the consistency, efficiency, and analytical power of river restoration monitoring, ultimately supporting more effective and adaptive management of fluvial systems.

# 3 What UAVs Deliver: Capabilities and Metrics for River Restoration

## 3.1 From Data Acquisition to Decision-Relevant Metrics

While UAV platforms are often described in terms of their sensors or flight capabilities, their value within river restoration is ultimately determined by the metrics they enable. Within the PRAGMO framework, monitoring is concerned not with the acquisition of imagery or point clouds per se, but with the generation of evidence that can be used to assess system condition, trajectory, and response to intervention. UAVs are therefore best understood as a means of transforming raw observations into spatially explicit, quantitative descriptors of river systems. This transformation occurs through a sequence of steps, beginning with data acquisition and progressing through processing and analysis to the derivation of metrics that correspond directly to PRAGMO indicators. The outputs of this workflow, such as digital elevation models, orthomosaics, and vegetation indices, are not endpoints in themselves, but intermediate products that support the extraction of meaningful information about geomorphological, hydrological, and ecological processes.

A key strength of UAV-based approaches lies in their ability to generate datasets that are both high resolution and spatially continuous, enabling the quantification of variability and pattern across entire river reaches (Figure 1). This is particularly important in restoration contexts, where the success of interventions is often expressed through increases in heterogeneity, connectivity, and process activity.

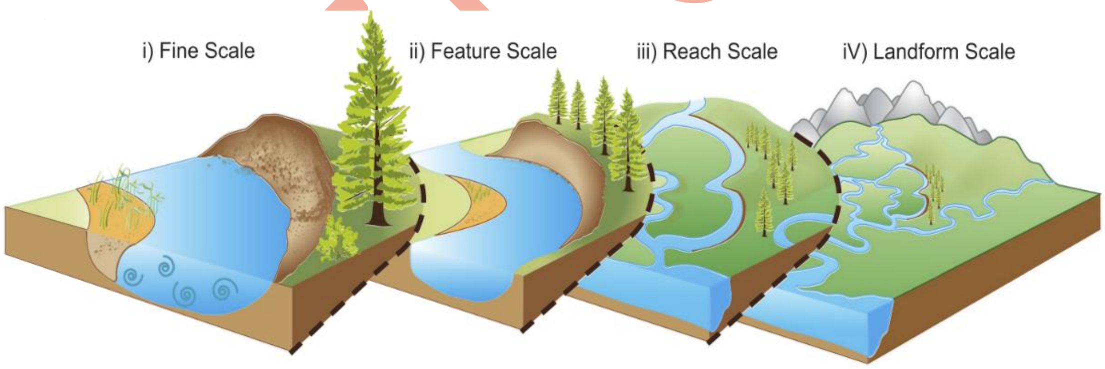


*Figure 1: Monitoring scales for river corridors: fine scale (i), feature scale (ii), reach scale (iii), and landform scale (iv) (Tomsett and Leyland, 2019).*

## 3.2 Core Capability Domains

The capabilities of UAV-based monitoring can be grouped into four broad domains, each corresponding to a set of PRAGMO-relevant metrics. These domains reflect not the technologies themselves, but the types of questions that UAV data can address.

### 3.2.1 Topographic and Morphological Characterisation

One of the most established applications of UAVs in fluvial environments is the generation of high-resolution topographic data. Using photogrammetric techniques such as Structure-from-Motion (SfM), or active sensors such as LiDAR, UAVs can produce detailed digital representations of terrain that capture channel form, floodplain morphology, and geomorphic features. These datasets enable the derivation of a range of metrics that are central to geomorphological assessment. Channel width, depth variability, and longitudinal gradient can be quantified with a level of spatial detail that is difficult to achieve using traditional survey methods. Orthomosaics and elevation models also support the identification and mapping of geomorphic units, including bars, riffles, pools, and areas of bank erosion.

Importantly, the spatial continuity of UAV-derived terrain models allows for the analysis of morphological heterogeneity, which is a key indicator of ecological function. Metrics such as the standard deviation of bed elevation or channel width can be used to characterise complexity and assess whether restoration interventions are achieving their intended outcomes.

### 3.2.2 Change Detection and Sediment Dynamics

A defining advantage of UAV-based monitoring is the capacity for repeatable data acquisition, enabling the quantification of change through time. By comparing successive terrain models or point clouds, practitioners can identify and measure patterns of erosion and deposition across a river reach. This approach, commonly implemented through DEMs of Difference (DoDs) or cloud-to-cloud comparison, provides a direct estimate of sediment flux and geomorphic activity. Volumetric changes can be calculated, allowing restoration outcomes to be expressed in quantitative terms such as net sediment gain or loss, bar migration, or channel adjustment. Such analyses are particularly valuable in assessing the effectiveness of interventions aimed at restoring natural sediment processes, for example through the removal of bank protection, the reintroduction of large wood, or the reconnection of floodplains. By providing spatially explicit evidence of process activity, UAV-derived change detection supports a more process-based evaluation of restoration success. However, it is important to note that the reliability of these metrics depends on careful control of uncertainty, particularly in relation to georeferencing accuracy and surface modelling. As such, the application of change detection methods requires consistent acquisition protocols and appropriate error thresholds.

### 3.2.3 Vegetation Structure and Habitat Mapping

UAVs are also well suited to the characterisation of riparian and in-channel vegetation, which plays a critical role in regulating hydraulic processes, sediment transport, and habitat availability. Using a combination of spectral imagery and three-dimensional data, UAVs can provide detailed information on both the extent and structure of vegetation.

Orthomosaics derived from RGB imagery enable the delineation of vegetation cover and the identification of features such as woody debris and macrophyte patches. When combined with multispectral or hyperspectral data, these observations can be extended to include indices of vegetation condition, such as NDVI, supporting the assessment of plant health and productivity.

Three-dimensional datasets, particularly those derived from LiDAR or SfM, allow for the construction of canopy height models, which provide a quantitative representation of vegetation structure. These models can be used to assess parameters such as vegetation height, density, and spatial arrangement, as well as to estimate shading patterns across the channel.

Together, these capabilities support the evaluation of habitat complexity and the role of vegetation in mediating physical processes. While UAV-based methods do not typically provide species-level identification, they offer a valuable means of contextualising field-based ecological surveys within a broader spatial framework.

### 3.2.4 Hydrological and Hydraulic Proxies

Although UAVs do not directly measure many hydrological variables, they can provide a range of proxy indicators that are relevant to flow dynamics and water–environment interactions. One example is the use of image velocimetry techniques, in which the movement of surface tracers is tracked across sequential imagery to estimate flow velocity fields. In addition, UAV-derived terrain models can be used to define channel geometry and boundary conditions for hydraulic modelling, while orthomosaics can support the delineation of water extent during flood events. Thermal imagery provides further capability, enabling the identification of groundwater inputs and thermal refugia, which are important for ecological functioning.

These approaches extend the scope of monitoring beyond static measurements, allowing practitioners to infer aspects of system behaviour that would otherwise require more complex or invasive instrumentation. However, such methods are sensitive to environmental conditions and should be applied with an understanding of their limitations.

## 3.3 Linking Capabilities to Metrics

The relationship between UAV capabilities and PRAGMO-relevant metrics is summarised in Table 3-1. This table emphasises the translation from data type to actionable information, highlighting the outputs that can be derived and their relevance to restoration monitoring.

*Table 3-1: UAV capabilities and associated metrics for river restoration monitoring*

| **Capability Domain** | **Data Type** | **Derived Metrics** | **PRAGMO Relevance** |
|---|---|---|---|
| Topography & morphology | SfM / LiDAR terrain models | Channel width, slope, cross-sections, geomorphic units | Channel form, habitat structure |
| Change detection | Multi-temporal DEMs / point clouds | Erosion/deposition volumes, sediment budgets, channel adjustment | Sediment dynamics, process activity |
| Vegetation & habitat | RGB, multispectral, LiDAR | Vegetation extent, NDVI, canopy height, shading | Riparian condition, habitat complexity |
| Hydrological proxies | RGB video, thermal imagery, DEMs | Surface velocity, water extent, groundwater inputs | Flow dynamics, connectivity |

## 3.4 Strengths and Appropriate Use

The principal strength of UAV-based monitoring lies in its ability to provide high-resolution, spatially continuous, and repeatable datasets, enabling the quantification of patterns and processes that are difficult to capture using conventional approaches. This makes UAVs particularly well suited to applications where spatial heterogeneity and temporal change are central to the monitoring objective.

At the same time, the effective use of UAVs requires a clear understanding of their limitations. Not all variables of interest can be measured directly, and the derivation of certain metrics may depend on assumptions or proxy relationships. As such, UAV-based approaches should be applied in a manner that is proportionate to the monitoring objectives and integrated with complementary methods where necessary.

UAVs deliver a suite of capabilities that extend across geomorphological, ecological, and hydrological domains, enabling the derivation of metrics that are directly aligned with PRAGMO indicators. Their value lies not in the technology itself, but in their ability to transform raw observations into actionable evidence, supporting a more quantitative and spatially explicit approach to river restoration monitoring.

## 3.5 Implementation Pathways for UAV-Based Monitoring

UAV-based monitoring can be implemented through a range of delivery models depending on project scale, technical capacity, and resource availability. These include in-house deployment, collaborative partnerships, or commissioning specialist providers.

Specialist facilities and providers, such as Environmental Sensing @ Southampton (ES@S; https://esas.soton.ac.uk/), provide integrated survey, analysis and provision of insight services that combine UAV platforms with complementary technologies (e.g. LiDAR, multibeam echosounding, and in situ measurements). Such approaches enable the delivery of end-to-end workflows, from survey design and data acquisition through to processing, analysis, and interpretation aligned with PRAGMO indicators.

Commissioned services may be particularly beneficial where:

- *high-resolution, multi-sensor datasets are required,*
- *sites are logistically complex or hazardous,*
- *repeat monitoring programmes are needed, or*
- *in-house expertise or processing capacity is limited.*

# 4 Case Studies: Application of UAVs within PRAGMO

## 4.1 Purpose and Role of Case Studies

The capabilities of UAV-based monitoring are most effectively understood when considered in the context of real-world application. While the preceding sections have outlined how UAVs can support PRAGMO through the generation of spatially explicit metrics, the practical value of these approaches lies in their ability to inform decision-making within specific river restoration contexts.

This section presents a series of case studies that demonstrate how UAV-based methods have been applied across contrasting river environments to support PRAGMO-aligned monitoring. Each example illustrates the translation of restoration objectives into measurable indicators, the application of UAV workflows to acquire relevant data, and the interpretation of resulting outputs in relation to system response and management outcomes.

## 4.2 A Place-Based Approach to Monitoring

River restoration is inherently place-specific, with outcomes shaped by local geomorphological setting, hydrological regime, land use, and management history. As such, the application of UAV-based monitoring cannot be considered in isolation from site context. The effectiveness of a given method depends on how well it captures the dominant processes and constraints operating within a particular system.

The case studies presented here therefore adopt a place-based perspective, highlighting how UAV-derived datasets are used to interrogate system behaviour within distinct environmental settings. This includes gravel-bed rivers characterised by active sediment transport, groundwater-dominated chalk streams with strong ecological sensitivity, and lowland systems where floodplain connectivity is a primary driver of function.

By grounding analysis in specific locations, the case studies demonstrate not only what UAVs can measure, but how those measurements relate to restoration objectives and outcomes in practice.

## 4.3 Alignment with PRAGMO

Each case study is explicitly structured around the PRAGMO framework, linking:

- *restoration objectives,*
- *selected indicators,*
- *UAV-based methods of data acquisition, and*
- *derived metrics used to evaluate system response.*

This alignment ensures that the examples are directly relevant to practitioners using PRAGMO, and illustrates how UAVs can be integrated within existing monitoring workflows without altering the underlying framework.

In particular, the case studies demonstrate how UAVs support the progression from objective definition through to evidence-based evaluation, enabling monitoring to move beyond descriptive assessment towards quantitative analysis of change.

The case studies have been selected to represent different domains of river restoration monitoring:

- *geomorphological processes and sediment dynamics,*
- *riparian vegetation structure and habitat function, and*
- *hydrological connectivity and floodplain behaviour.*

Together, these examples reflect the breadth of applications through which UAVs can support PRAGMO, while also illustrating the importance of integrating multiple lines of evidence in understanding system response.

## Case Study 1 River Itchen (Winchester) – Riparian Shading and Water Temperature

**Context**: A 500 m reach of the River Itchen in Winchester characterised by a multi-channel planform and heterogeneous riparian vegetation, including grasses, shrubs, and mature trees. Active vegetation management (weed cutting and bank maintenance) creates spatial variability in shading conditions, influencing in-channel thermal regimes.

**Objective**: To quantify the spatial distribution of riparian shading and assess its influence on surface water temperature, supporting restoration planning and evaluation of vegetation management strategies.

**Approach**: A multi-sensor UAV survey was undertaken using a DJI Matrice 300 RTK equipped with LiDAR (Topodrone 100), RGB (DJI Zenmuse P1) and thermal (DJI Zenmuse H20T) sensors.

Data were collected using a terrain-following cross-grid flight pattern and georeferenced using PPK with GCP validation. Processing combined LiDAR-derived terrain and canopy models with RGB classification and calibrated thermal imagery to produce integrated spatial datasets.

**Key Outputs**: High-resolution orthomosaic (2 cm); Digital Terrain Model (DTM) and Digital Surface Model (DSM); Canopy Height Model (CHM); Classified land cover map (grass, shrubs, trees, water); Spatially explicit shading maps (multi-time and seasonal scenarios); Channel-constrained thermal imagery

**Key Findings**: Shading patterns vary significantly between channels due to vegetation structure and planform geometry; Larger canopy elements (>4 m$^2$) exert a dominant control on shading extent; Thermal imagery reveals clear spatial variability in surface water temperature, with shaded areas generally associated with cooler conditions; Combined datasets enable direct linkage between vegetation structure, shading, and thermal response.

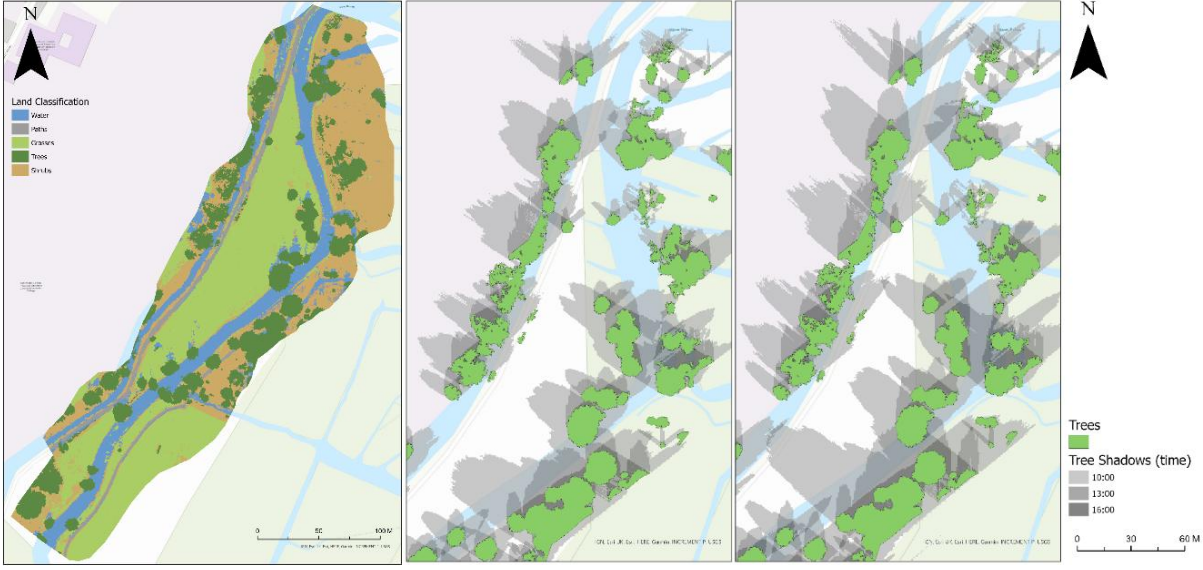


*Figure 2: (Left) Land cover classification map of the study site. Canopy shading maps at 10:00, 13:00, and 16:00 on 01/04/25 (centre) and 01/10/25 (right). Green polygons indicate tree cover greater than 4 m$^2$.*

**Implications for Restoration Practice**: Supports evidence-based riparian management, including targeted tree planting or selective clearance; Enables scenario testing of shading interventions prior to implementation; Provides a framework for monitoring restoration outcomes through time; Identifies potential thermal refugia and areas of thermal stress

**Key Advantages of UAV Approach**: High-resolution, reach-scale coverage of vegetation and channel conditions; Repeatable surveys enabling temporal analysis; Integration of structural (LiDAR), spectral (RGB), and thermal datasets; Non-intrusive data collection in sensitive or inaccessible environments

**Considerations**: Accuracy dependent on vegetation conditions (best under leaf-off for terrain modelling); Thermal data requires calibration for quantitative analysis; Processing workflows require technical expertise and computational capacity; High-specification sensors increase cost, though lower-cost alternatives may provide partial capability

**Take-Home Message**: UAV-based workflows enable the quantitative linkage between riparian vegetation, shading, and thermal regimes, providing a powerful tool for designing, targeting, and evaluating river restoration interventions within a PRAGMO framework.

## Case Study 2 River Stiffkey (Norfolk) – Morphological Baselining

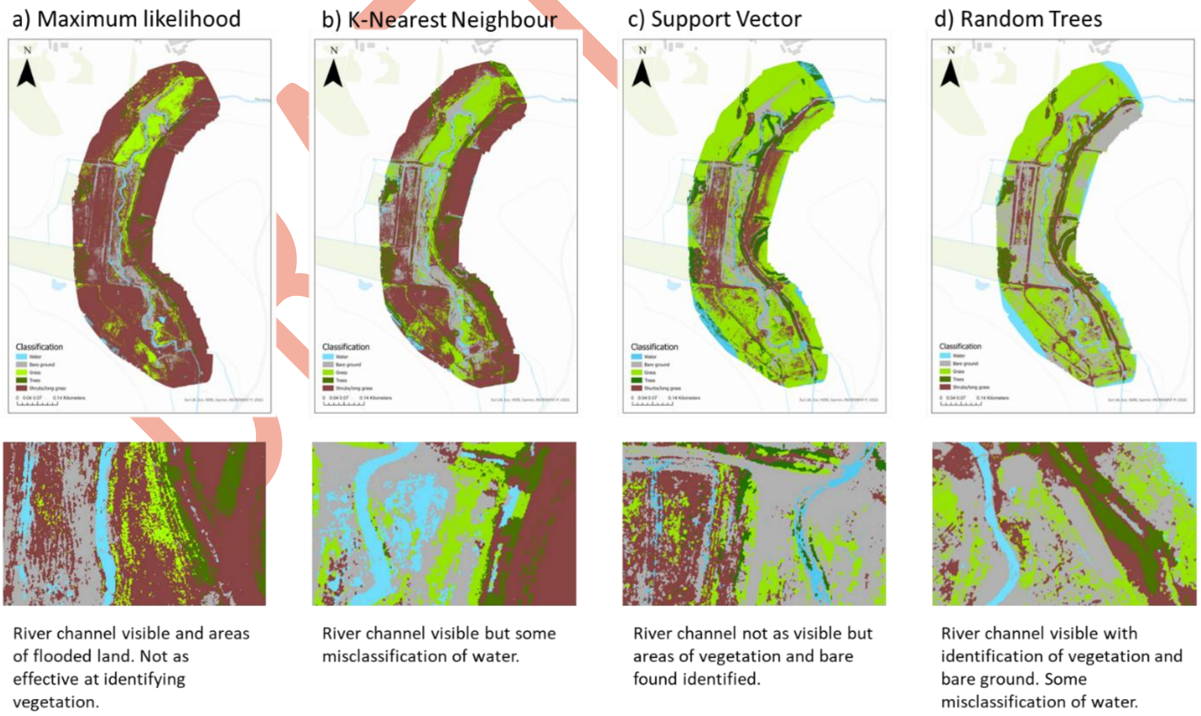
**Context**: A restored reach of the River Stiffkey in Norfolk, managed by the Norfolk Rivers Trust. The site forms part of a wider restoration programme, including channel re-meandering and the introduction of large woody material to enhance habitat complexity. UAV surveys were conducted immediately post-restoration to establish a high-resolution morphological baseline.

**Objective**: To develop a quantitative baseline of channel morphology and habitat structure following restoration, enabling long-term monitoring of geomorphic adjustment, vegetation development, and restoration success.

**Approach**: A multi-sensor UAV survey was undertaken using a DJI Matrice 300 RTK equipped with LiDAR (Topodrone 100) and RGB imagery (DJI Zenmuse P1).

Data were collected using terrain-following cross-grid flights, with the site divided into segments to comply with visual line-of-sight (VLOS) regulations. Surveys were georeferenced using PPK workflows with Ground Control Points (GCPs) and complemented by GNSS RTK cross-section surveys for validation. Processing integrated LiDAR-derived terrain models, photogrammetric outputs, and GIS-based analysis to produce a comprehensive suite of geomorphic and ecological datasets.

**Key Outputs**: High-resolution orthomosaics of the restored reach; Digital Terrain Model (DTM) and Digital Surface Model (DSM); Canopy Height Model (CHM); Cross-section profiles (GNSS and SfM-derived); Woody debris inventory and spatial distribution maps; Classified land cover maps (multiple classification approaches); Bathymetric estimates derived from through-water SfM



River channel visible and areas of flooded land. Not as effective at identifying vegetation.

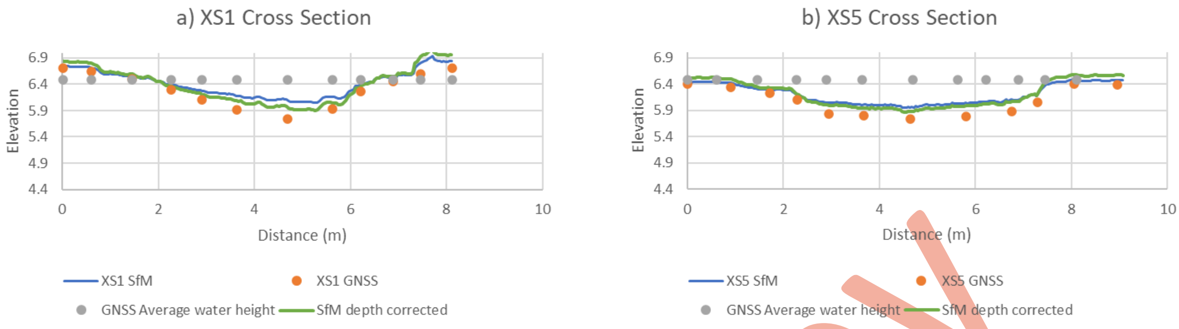
River channel visible but some misclassification of water.

River channel not as visible but areas of vegetation and bare found identified.

River channel visible with identification of vegetation and bare ground. Some misclassification of water.

*Figure 3: Land classifications with strengths and weaknesses for the river Stiffkey using different methods: a) maximum likelihood, b) K-Nearest Neighbour, c) Support Vector and d) Random Tree.*

**Key Findings**: The re-meandered channel exhibits spatially variable morphology, reflecting early-stage geomorphic adjustment; Cross-section analysis demonstrates strong agreement between GNSS and UAV-derived datasets, supporting the reliability of UAV methods; Large woody material is clearly identifiable and can be quantified spatially, enabling monitoring of accumulation and morphological influence; Land classification highlights areas of disturbance associated with restoration works, providing a baseline for tracking vegetation recovery



**Implications for Restoration Practice**: Provides a robust morphological baseline against which future channel evolution can be quantified; Enables transition from discrete (cross-section-based) to spatially continuous monitoring; Supports assessment of large wood dynamics and associated geomorphic effects; Facilitates monitoring of vegetation recovery and habitat development, including alignment with biodiversity and carbon objectives; Offers a framework for long-term, repeatable monitoring within PRAGMO

**Key Advantages of UAV Approach**: High-resolution, reach-scale coverage of channel and floodplain; Integration of terrain, vegetation, and habitat data; Repeatable datasets suitable for change detection; Strong agreement with ground-based survey methods

**Considerations**: Vegetation may limit terrain detection in later stages of recovery; Processing workflows require computational resources and expertise; Through-water SfM bathymetry is dependent on water clarity and surface conditions; Higher-specification sensors (e.g. LiDAR) increase cost, though lower-cost alternatives may provide partial capability

**Take-Home Message**: UAV-based surveying provides a step change in morphological monitoring, enabling high-resolution, spatially continuous baseline datasets that support robust, long-term evaluation of river restoration outcomes within a PRAGMO framework.

# 5 Limitations, Challenges, and Best Practice

The integration of UAVs within river restoration monitoring offers substantial benefits, but their effective use depends on a clear understanding of both their capabilities and limitations. Consistent with the principles of the PRAGMO, monitoring approaches should be objective-led, proportionate, and aligned with decision-making requirements, rather than driven by technological availability.

UAVs are most effective where they enable measurements that would otherwise be impractical, improve the spatial representation of monitoring data, or enhance the ability to quantify change. However, their deployment must be carefully considered within the operational, technical, and regulatory context of each project.

## 5.1 Methodological, Operational, and Regulatory Constraints

UAV-based monitoring is subject to a range of methodological, operational, and regulatory constraints that influence both data quality and practical implementation. From a methodological perspective, photogrammetric approaches are limited in their ability to penetrate dense vegetation, reducing the accuracy of terrain models in heavily vegetated environments. As a result, optimal performance is often achieved under leaf-off conditions, while sites with persistent canopy cover may remain challenging (Hamshaw et al., 2017). Similarly, the detection of submerged features is dependent on water clarity and surface conditions, limiting the effectiveness of UAV-based bathymetry in turbid or high-energy systems.

UAV-derived datasets are also constrained in their ability to capture species-level ecological information, particularly in complex habitats. While structural and spectral data can be derived, detailed ecological assessments typically require integration with field-based surveys or alternative sensing approaches (Tomsett and Leyland, 2019). In addition, UAV surveys provide discrete temporal snapshots of system state. Although repeat surveys can address this limitation, short-term variability associated with dynamic processes may not be fully resolved unless monitoring frequency is sufficiently high.

Operational challenges arise during data acquisition and are common across sensor types (Woodget et al., 2017). Image quality may be affected by motion blur or platform instability, while environmental conditions, including wind, illumination, and water surface characteristics, can influence both flight safety and data consistency. Accurate georeferencing (see section 6.3) remains essential, often requiring the use of Ground Control Points (GCPs) or RTK/PPK systems, which introduce additional field effort and logistical complexity.

Data processing presents further constraints. High-resolution UAV surveys generate large datasets that require substantial storage capacity, processing time, and computational resources. Errors introduced during image alignment, georeferencing, or surface reconstruction may propagate into derived products, particularly in change detection analyses. Robust quality control procedures and reproducible workflows are therefore essential to ensure reliability.

Regulatory and ethical considerations also play a critical role. UAV operations in the UK are governed by the Civil Aviation Authority (CAA), with requirements relating to operator registration, pilot competency, and operational restrictions. These constraints influence where and how UAVs can be deployed, particularly in proximity to people, infrastructure, and controlled airspace. Ethical considerations, including privacy and data protection, must also be addressed when operating in areas with public access. Compliance with these requirements is essential and may influence survey design and feasibility.

## 5.2 Cost, Accessibility, and Key Challenges

The adoption of UAV-based monitoring involves a combination of technical, financial, and environmental challenges. While UAVs are often presented as cost-effective, their implementation requires investment not only in UAV platforms, but also in sensor payloads, software licences, field equipment (e.g. GCPs and dGNSS systems), maintenance, insurance, and training (Woodget et al., 2017). These upfront costs can limit accessibility, particularly for smaller organisations.

Data quality is also strongly influenced by environmental conditions, with vegetation characteristics playing a key role. For example, terrain representation is typically most accurate under leaf-off conditions, and performance may be reduced in areas where vegetation is present year-round (Hamshaw et al., 2017). Furthermore, UAV-based approaches may be less effective for resolving detailed vegetation structure compared to some traditional or alternative sensing techniques (Tomsett and Leyland, 2019).

Across workflows, these challenges can be broadly grouped into three categories:

- *Acquisition challenges, including image quality, environmental variability, georeferencing requirements, and regulatory constraints*
- *Processing challenges, including data volume, computational demands, and error propagation*
- *General challenges, including cost, accessibility, and limitations in capturing certain ecological characteristics*

Despite these constraints, ongoing technological developments continue to improve the accessibility and capability of UAV systems, reducing costs and simplifying data acquisition and processing workflows (Acharya et al., 2021; Hemmelder et al., 2018).

## 5.3 Best Practice and Recommendations for Application

When applied appropriately, UAVs offer a transformative approach to river restoration monitoring, combining high spatial resolution with rapid and repeatable data acquisition. The datasets produced are comparable in accuracy to those obtained through traditional techniques such as TLS and GPS (Hamshaw et al., 2017), while offering substantial advantages in spatial coverage and efficiency.

A key strength of UAV-based monitoring lies in its repeatability and programmability. Scheduling surveys at regular intervals allows system change to be tracked and quantified through time, supporting robust multi-temporal analysis (Tomsett and Leyland, 2019). The use of flight planning software further enhances consistency between surveys and reduces operational complexity (Langhammer, 2019).

UAV systems are also highly adaptable to context, with sensor selection and processing workflows tailored to specific monitoring objectives. For example, in environments with relatively low surface complexity, reducing DEM resolution can decrease processing time while maintaining sufficient accuracy for analysis (Langhammer et al., 2017).

The integration of multiple sensors provides further analytical benefits. Combining LiDAR and SfM-derived datasets enables improved representation of both terrain and vegetation structure (Tomsett and Leyland, 2023), while integrating SfM with optical bathymetry supports the development of detailed fluvial terrain models (Javernick et al., 2014). Similarly, combining orthophotos with 3D models allows more comprehensive interpretation of channel features and habitat structure (Langhammer et al., 2023).

Importantly, UAV-based approaches should be integrated with field-based methods to ensure that both spatial patterns and site-specific detail are captured. This combined approach aligns with PRAGMO principles and supports more robust, evidence-based monitoring.

## 5.4 Summary

UAVs provide a powerful and versatile tool for river restoration monitoring, enabling high-resolution, spatially explicit, and repeatable data collection across entire river corridors. They support quantitative assessment of system change, improve safety and efficiency in data acquisition, and enhance communication with stakeholders.

However, their effective application requires careful consideration of methodological limitations, operational constraints, data processing requirements, and regulatory compliance. By adopting a structured, objective-led approach and integrating UAVs with established field-based methods, practitioners can ensure that these technologies enhance, rather than complicate, monitoring within the PRAGMO framework. In doing so, UAVs provide a strong foundation for advancing more quantitative, scalable, and adaptive approaches to river restoration monitoring.

# 6 Technical Appendix: Platforms, Sensors, Field Deployment and Processing Techniques.

Uncrewed Aerial Vehicles (UAVs) are a rapidly developing and increasingly valuable tool for river restoration, capable of capturing data across multiple spatial scales, from fine-scale to reach- and landform-scale, and across multiple temporal scales (Acharya *et al.*, 2021).

Over the past 15 years (2010–2025), UAV systems have undergone significant development, evolving from complex platforms requiring specialist knowledge and offering limited flight times, to readily deployable systems equipped with a range of sensor packages and integrated processing routines. This progression has enabled UAVs to transition rapidly from niche applications to widely adopted tools within environmental monitoring.

Within river restoration, the diversity of sensors that can be mounted on UAV platforms supports a broad range of applications across pre-, during-, and post-restoration phases. This versatility makes UAVs particularly well suited to supporting restoration practitioners, allowing data acquisition to be tailored to specific monitoring objectives and site conditions.

The following guide outlines the key elements of UAV platforms and sensors, aviation safety considerations, and a range of deployment scenarios relevant to river restoration. It is not intended to provide an exhaustive technical manual for specific UAV applications, but rather to offer an overview that enables practitioners to explore and apply UAV-based approaches in a structured and informed manner.

## 6.1 Platforms

There are two main types of UAV platforms: fixed-wing and multi-rotor, both of which have distinct advantages and limitations and are suited to different applications (Table 6-1). Fixed-wing aircraft operate in a similar manner to traditional aeroplanes, using aerodynamic lift generated over the wings to remain airborne. In contrast, multi-rotor aircraft generate lift through a series of motors driving propellers, with configurations ranging in number, although most commonly comprising four rotors (quadcopters). Within the fixed-wing category, there is a growing class of VTOL (Vertical Take-Off and Landing) systems, which combine the extended range of fixed-wing platforms with the operational flexibility of vertical take-off and landing.

UAV platforms may be powered by either battery or fuel-based energy sources. The majority of commercially available multi-rotor and fixed-wing systems are battery-powered, reflecting their ease of use and suitability for short- to medium-duration surveys. Larger UAV platforms, particularly those designed for extended flight times or increased payload capacity, are more likely to utilise liquid fuel.

Within the UK, aircraft released after 1 January 2026 are assigned class marks that determine the operational category in which they can be flown, ranging from UK0 to UK6. These classifications are based on factors including weight, technical functionality, and safety features. Further information is available on the Civil Aviation Authority (CAA) website (https://www.caa.co.uk/drones/getting-started-with-drones-and-model-aircraft/class-marks/#), or by searching for “UK CAA UAV classes”.

*Table 6-1: The two main types of UAV platforms. Advantages and disadvantages are relative to the other type of UAV. For a detailed description see Hackney and Clayton (2015).*

| Type | Description | Advantages | Disadvantages |
|---|---|---|---|
| Fixed-wing | • Uses fixed wings to generate lift and control flight<br>• Launched from the ground (often via hand or catapult)<br>• 1-3 m wide | • Longer flight endurance due to higher fuel efficiency and flight speed<br>• Greater payload capacity<br>• Can cover greater areas | • Requires greater space for take off<br>• Lacks manoeuvrability |
| Rotary-wing or Multi-rotor | • Use one or more rotors to generate lift and control flight<br>• < 1 m wide | • Vertical take-off and landing<br>• Quicker deployment<br>• Higher stability in windy conditions<br>• Higher quality datasets | • Limited flight endurance<br>• Lower flight speeds |

## 6.2 Sensors

A wide range of sensors, both active and passive, can be deployed on UAV platforms, each producing datasets suited to different applications across river restoration. These datasets can support activities from restoration design and implementation through to monitoring and evaluation of outcomes.

Table 6-2 outlines the principal sensors that can be integrated with UAV systems and their associated applications. While each sensor offers specific advantages, no single sensor is suitable for all use cases. It is therefore important to define the key monitoring questions at the outset and select the most appropriate sensor or combination of sensors accordingly.

*Table 6-2: Sensors which can be used with UAVs. For more detail, see Acharya et al. (2021); Colomina and Molina (2014); Manfreda et al. (2018).*

| **Sensor** | **Data Collection Objectives** | **Applications** | **Advantages** | **Disadvantages** | **Recommendations** | **Costs** | **Examples of use** |
|---|---|---|---|---|---|---|---|
| RGB Imagery | Produce high-resolution orthomosaics & DEMs | - Mapping channel features e.g. vegetation, woody debris, anthropogenic modifications<br>- Assessing water quality e.g. floating materials, foam, eutrophication<br>- Velocity measurements (via velocimetry) | - High resolution (depending on UAV)<br>- Relatively inexpensive and can be done using low-cost UAVs<br>- Easy to integrate with different platforms<br>- Relatively efficient | - Limited capture of non-visible data e.g. under vegetation/ turbid water (Langhammer, 2019)<br>- Low spectral resolution | Select appropriate sensor size, focal length, and shutter type for use | **Sensor**: | (Backes *et al.*, 2020; Koutalakis *et al.*, 2019; Langhammer, 2019; Langhammer *et al.*, 2023) |
| Multispectral | Produce imagery in wavelengths beyond the visible spectrum to derive vegetation and water indices | - Vegetation mapping & classification<br>- Bathymetry<br>- Water quality assessment e.g. turbidity & algal bloom monitoring<br>- Flood monitoring e.g. water extent | - Can be used to derive indices for quantitative vegetation and water monitoring<br>- Can detect and delineate aquatic vegetation | - Higher sensor & panel cost<br>- Sensitive to weather; needs atmospheric correction<br>- Coarser resolution than RGB<br>- Limited detection of aquatic vegetation in turbid water | Ensure sensor has been correctly calibrated | **Sensor**: | (Song and Park, 2020; Tomsett and Leyland, 2021) |
| Hyperspectral | Obtain narrow, contiguous bands for detailed spectral analysis | - Vegetation mapping and classification<br>- Bathymetry<br>- Water quality assessment e.g. turbidity & algal bloom monitoring<br>- Flood monitoring e.g. water extent<br>- Hydrochemistry | - Greater spectral resolution than multispectral sensors | - Very expensive systems (higher cost than RGB and multispectral)<br>- Low spatial resolution<br>- Limited compatibility with standard UAV software packages? | Ensure sensor has been correctly calibrated | **Sensor**: | (Cai *et al.*, 2022; Liu *et al.*, 2021; You and Kim, 2021) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | - Needs robust atmospheric correction | | | |
| Thermal Imagery | Map surface water temperatures | - Surface water temperature mapping<br>- Identification of groundwater discharge<br>- Wetland mapping | - Can sense a wide range of temperatures | - Low spatial resolution<br>- Sensitive to surface roughness changes | Fly at night/early morning for max contrast | **Sensor**: | (Aicardi *et al.*, 2017; Sedano-Cibrián *et al.*, 2022) |
| Microwave Radar | Acquire passive brightness-temperature maps and active backscatter data | - Flood monitoring under cloudy conditions<br>- Water level estimation<br>- Wetland monitoring | - Operational in poor visibility<br>- Can penetrate clouds/fog | - Low spatial resolution<br>- Sensitive to surface roughness<br>- Relatively expensive | | **Sensor**: | (Ye *et al.*, 2024) |
| NIR LiDAR | Generate point clouds to map topography and vegetation structure | - Vegetation classification and monitoring<br>- Wood-debris source identification<br>- Topographic modelling<br>- Water temperature assessment | - Penetrates vegetation effectively<br>- High resolution | - Cannot penetrate water<br>- High cost<br>- Data quality varies with vegetation conditions | Combine with Green band Lidar or SfM for full river corridor mapping | **Sensor**: | (Dufour *et al.*, 2013; Tomsett and Leyland, 2021) |
| Green-band LiDAR | Generate point clouds to map bathymetry and other channel characteristics | - Bathymetric modelling<br>- In-channel feature identification e.g. pools and riffles | - Can penetrate water | - Less effective than NIR LiDAR at penetrating vegetation<br>- High cost<br>- Point cloud has lower density than NIR | Combine with NIR Lidar for full river corridor mapping | **Sensor**:<br>**Field**:<br>**Processing:** | (Kinzel *et al.*, 2007) |

## 6.3 Georeferencing

Without georeferencing, data collected using UAVs remains in 'image space'. While such data may still be visually interpreted, its utility is limited, as accurate measurement and integration within GIS-based workflows cannot be undertaken. The use of differential Global Navigation Satellite Systems (dGNSS or dGPS), in combination with Ground Control Points (GCPs), is a commonly applied approach to georeferencing UAV datasets (Hackney and Clayton, 2015; Tomsett and Leyland, 2021).

### 6.3.1 Coordinate Systems

A basic understanding of coordinate systems is essential where UAV-derived outputs are intended to support spatial analysis, decision-making, or integration with existing datasets. Two key considerations arise during data collection and processing: (1) the horizontal coordinate system, and (2) the vertical coordinate system.

For horizontal positioning, outputs are typically represented in a projected coordinate system, such as British National Grid (OSGB) or an appropriate UTM zone (e.g. 30N or 31N). Data acquired in WGS84 can be projected into these systems. It is important to assess the coordinate reference systems used by existing datasets and align UAV outputs accordingly. In the UK, many datasets are provided in OSGB format, which often facilitates data sharing and integration; however, this should be confirmed prior to processing to ensure optimal alignment.

Vertical referencing is more complex, as it may be based on either an ellipsoid (a mathematically defined representation of the Earth's shape) or a geoid (an approximation of mean sea level accounting for variations in gravitational potential). WGS84 elevations are typically ellipsoid-based, while many datasets incorporate geoid models, such as Earth Gravitational Models (EGM) produced by the National Geospatial-Intelligence Agency. In the UK, vertical data are commonly referenced to Ordnance Datum Newlyn (ODN), which represents a geoid-based height system. Care must therefore be taken to ensure consistency between vertical reference systems when integrating datasets.

### 6.3.2 GCPs and CPs

Ground Control Points (GCPs) are typically well-defined, easily visible targets or fixed features within the landscape that can be clearly identified in UAV imagery. The number and distribution of GCPs required will depend on the objectives and scale of the survey (Hackney and Clayton, 2015). Their positions are commonly determined using dGPS or through an arbitrary coordinate framework established using a total station or similar instrument (Hackney and Clayton, 2015).

dGPS systems consist of a base station and rover and can be deployed across a range of environments to provide accurate and efficient positioning data (Young, 2012). A variety of systems are available, from established platforms such as Leica dGPS 1200 to more recent, cost-effective solutions such as the Reach RS2+. Regardless of the system used, it is essential to verify and maintain positional accuracy, as this underpins the reliability of all subsequent analyses.

### 6.3.3 RTK vs PPK vs NoPK

Accurate georeferencing is fundamental to the effective use of UAV-derived datasets, particularly where outputs are intended for quantitative analysis, change detection, or integration with other spatial data. In addition to the use of Ground Control Points (GCPs), positional accuracy can be improved through onboard GNSS correction techniques, most commonly Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK). These approaches differ in how correction data are applied and have implications for workflow, accuracy, and operational flexibility.

RTK positioning applies corrections to GNSS data in real time during the UAV flight. This is typically achieved through a base station located on-site or via a network-based correction service (e.g. NTRIP), allowing the UAV to record highly accurate positional information for each image at the point of acquisition. RTK workflows can significantly reduce the number of GCPs required, and in some cases enable surveys to be conducted without GCPs where relative accuracy is sufficient. However, RTK performance is dependent on maintaining a stable communication link between the rover (UAV) and the correction source, and may be affected by signal obstruction, terrain, or network availability.

PPK positioning, in contrast, applies GNSS corrections after data acquisition using recorded satellite observations from both the UAV and a reference base station. This approach removes the need for a continuous communication link during flight, increasing robustness in environments where real-time correction signals may be unreliable or unavailable. PPK workflows are generally considered to provide comparable or, in some cases, higher positional accuracy than RTK, particularly where post-processing allows for quality control and optimisation of correction parameters (James et al., 2017). However, PPK introduces additional processing steps and requires careful management of GNSS data and timing synchronisation.

In the absence of RTK or PPK (here referred to as No Positional Kinematic; NoPK), UAV positioning relies solely on standard GNSS data recorded by the onboard receiver. While this approach is sufficient for general mapping and visualisation, positional accuracy is typically limited to metre-scale, which is insufficient for many river restoration applications, particularly those involving quantitative measurement or multi-temporal analysis. In such cases, the use of GCPs becomes essential to achieve acceptable levels of accuracy (Hackney and Clayton, 2015).

The choice between RTK, PPK, and NoPK approaches should be guided by the objectives of the survey, required accuracy, site conditions, and available resources. For high-precision applications such as change detection or terrain modelling, RTK or PPK methods are strongly recommended, ideally in combination with a reduced number of well-distributed GCPs to provide independent validation. For lower-precision applications, such as reconnaissance mapping or stakeholder communication, NoPK approaches may be sufficient, provided that their limitations are recognised.

In practice, hybrid approaches are increasingly common, combining RTK or PPK positioning with a small number of GCPs and independent check points (CPs) to ensure both accuracy and quality assurance. This approach aligns with best practice in UAV-based surveying, balancing efficiency with reliability and ensuring that datasets are suitable for quantitative analysis (James et al., 2020; Tomsett and Leyland, 2021).

## 6.4 Practical application: Use of UAVs in the field

The effective deployment of UAVs for river restoration monitoring requires a structured and repeatable workflow that integrates regulatory compliance, survey design, field deployment, and data processing. Adherence to a clearly defined workflow ensures that datasets are collected safely, consistently, and in a manner aligned with monitoring objectives, thereby supporting robust analysis and comparison across sites and time periods.

### 6.4.1 Regulatory Considerations

Prior to any UAV deployment, it is essential to review and comply with the regulations governing their use. In the UK, these are defined by the Civil Aviation Authority (CAA), with detailed guidance provided in CAP2320. Table 6-3 summarises the key operational requirements for UAVs above and below 250 g.

Across all UAV operations, several core principles apply. Flights must not be conducted within Flight Restriction Zones (FRZs) without appropriate permissions, and operators must ensure that the aircraft is fit for flight. Environmental conditions should be assessed carefully, and flights should not proceed where wind, precipitation, or visibility may compromise safety or data quality. While some operational constraints, such as extended visual line-of-sight, may be addressed through additional training and certification, these should be considered at the planning stage.

*Table 6-3: The key requirements for operating drones above and below 250 g*

| Requirements | Above 250 g | Below 250 g |
|---|---|---|
| **Identification** | Operator ID<br>Flyer ID | Operator ID |
| **Flying limits** | Height limit of 120 m<br>Visual line of sight (~500 m)<br>Minimum 50 m from uninvolved people<br>Minimum 150 m from built-up areas<br>No flights over crowds | Height limit of 120 m<br>Visual line of sight (~500 m)<br>No flights over crowds |

### 6.4.2 Workflow for UAV Data Acquisition

UAV-based data collection should follow a structured sequence of steps, as illustrated in Figure 4, to ensure that datasets are suitable for subsequent analysis and aligned with monitoring objectives (Rusnák et al., 2018).

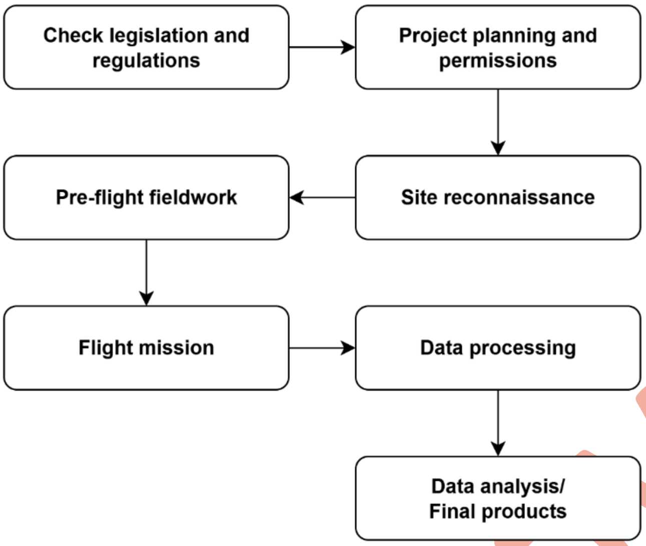


*Figure 4: The general workflow for data acquisition using UAVs. For more detail see Rusnák et al. (2018).*

### 1. Check legislation and regulations

Before any fieldwork is undertaken, it is essential to confirm that UAV operations are permissible at the site. This includes identifying any airspace restrictions, verifying proximity to Flight Restriction Zones, and ensuring that all required permissions have been obtained. Operators must also confirm that they hold the necessary certification (e.g. Operator ID, Flyer ID) and that the UAV platform complies with current regulatory classifications. Early consideration of regulatory constraints is critical, as these may influence site selection, survey design, or feasibility.

### 2. Project planning and permissions

At this stage, the objectives of the survey should be clearly defined in relation to the monitoring requirements (see Section 2.5). This includes identifying the indicators to be measured, the spatial and temporal resolution required, and the appropriate outputs. Based on these objectives, decisions can be made regarding sensor selection, flight altitude, image overlap, and survey extent. Permissions from landowners, regulatory bodies, or other stakeholders should be obtained where necessary. Effective planning at this stage ensures that data acquisition is proportionate and aligned with the intended analysis.

### 3. Site reconnaissance

A detailed assessment of the site should be undertaken prior to data collection. This includes identifying suitable take-off and landing locations, assessing terrain and access constraints, and recognising potential hazards such as overhead cables, tall vegetation, water bodies, or nearby infrastructure. Reconnaissance also provides an opportunity to refine the flight plan, ensuring adequate coverage of the study area while maintaining safe operating conditions. Where repeat surveys are planned, it is beneficial to establish consistent take-off locations and flight extents.

### 4. Pre-flight fieldwork

Pre-flight preparation is critical for ensuring data quality. Where high positional accuracy is required, Ground Control Points (GCPs) should be deployed across the study area in a well-distributed configuration (see Section 5.3). The UAV platform and sensors should be checked thoroughly, including battery status, firmware updates, and calibration of cameras or other sensors. Weather conditions should be reassessed immediately prior to flight, with particular attention to wind speed, cloud cover, and lighting conditions, as these can influence both safety and data quality. In publicly accessible areas, appropriate signage should be installed to inform members of the public and minimise disturbance.

**5. Flight mission**
During the flight mission, the UAV is deployed according to the predefined flight plan, capturing imagery or other sensor data across the study area. Operators should maintain continuous awareness of the UAV's status, including battery levels, telemetry, and positioning accuracy. Environmental conditions should be monitored throughout the flight, and operations should be paused if conditions deteriorate. Attention should also be given to potential hazards such as other airspace users (e.g. helicopters), birds, or unexpected human activity. Maintaining consistent flight parameters, such as altitude, speed, and image overlap, is essential for ensuring comparability between datasets.

**6. Data processing**
Following data acquisition, datasets should be reviewed to assess completeness and quality, including image coverage, overlap, and clarity. Processing workflows are then applied to generate the required outputs, such as orthomosaics, point clouds, or digital elevation models (see Section 2.6). This stage typically involves image alignment, georeferencing, noise filtering, and model generation. Quality control procedures should be applied throughout, including verification of GCP accuracy and inspection of model artefacts. Processing decisions should be documented to ensure reproducibility, particularly for multi-temporal analyses.

**7. Data analysis and final products**
The final stage involves extracting relevant metrics and information from the processed datasets in accordance with the monitoring objectives. This may include feature mapping, calculation of terrain metrics, change detection, or classification of vegetation or habitat types. Outputs should be prepared in formats suitable for integration within GIS platforms and aligned with PRAGMO indicators. Where appropriate, results should be validated against independent data sources or field observations. The resulting products form the basis for interpretation, reporting, and decision-making within the restoration framework.

## 6.5 Data Processing and Analysis

A range of data processing techniques are available to transform UAV-derived imagery and sensor data into outputs suitable for river restoration monitoring and analysis. These techniques underpin the extraction of quantitative information on channel morphology, sediment dynamics, vegetation structure, and hydrological processes, and are therefore central to the application of UAVs within a PRAGMO framework.

The following sections provide a brief overview of the principal processing approaches commonly used in river environments, outlining their purpose and general application. A concise summary of these techniques, including their key advantages, limitations, and typical use cases, is provided in Table 6-4 to support method selection and practical implementation.

### 6.5.1 Orthophoto Generation

Orthophoto generation is one of the most widely applied UAV processing techniques, producing georeferenced, spatially continuous imagery that can be used for measurement, mapping, and visualisation (Carrivick and Smith, 2019). Orthophotos have been used extensively to map river morphology and support geomorphological interpretation across a range of environments (Woodget et al., 2017; Rusnák et al., 2018).

The process involves importing overlapping imagery into photogrammetric software (e.g. Agisoft Metashape, Pix4D), aligning images, and generating a stitched, georeferenced mosaic. The quality of the resulting orthophoto is dependent on image overlap, georeferencing accuracy, and illumination conditions. Orthophotos provide full site coverage at high spatial resolution and are compatible with a wide range of sensors. They are therefore widely used for baseline mapping and monitoring applications, including post-restoration assessment (Langhammer et al., 2023).

### 6.5.2 Structure-from-Motion (SfM) and Point Cloud Generation

Structure-from-Motion (SfM) photogrammetry enables the reconstruction of three-dimensional river environments from overlapping imagery (Westoby et al., 2012; Woodget et al., 2017). It has been widely applied to map river morphology, terrain structure, and geomorphic change (Backes et al., 2020; Evans et al., 2022). SfM workflows involve image acquisition, feature matching, sparse and dense point cloud generation, and georeferencing. A minimum of 60% overlap is typically required to ensure robust reconstruction (Dietrich, 2016). SfM provides a cost-effective approach to generating high-resolution topographic data and has been successfully applied in monitoring dynamic environments such as glacial streams (Backes et al., 2020) and assessing geomorphic responses to restoration interventions (Evans et al., 2022). However, its performance is limited in densely vegetated environments and under variable lighting conditions, and it requires substantial post-processing.

### 6.5.3 Digital Elevation Model (DEM) Generation

Digital Elevation Models derived from UAV data are fundamental to river restoration analysis, supporting the quantification of channel morphology, floodplain structure, and hydraulic processes. SfM-derived DEMs have been widely used to characterise riverine landscapes and channel geometry (Javernick et al., 2014; Rusnák et al., 2018), while LiDAR-based approaches provide enhanced capability in vegetated environments and for structural analysis (Dufour et al., 2013; Tomsett and Leyland, 2021). DEM-based analysis also underpins hydrodynamic modelling applications, where high-resolution terrain data are used to simulate flow processes and inundation patterns (Langhammer et al., 2017).

### 6.5.4 Change Detection

Change detection using UAV-derived datasets enables the quantification of geomorphic processes such as erosion and deposition through time. This approach has been widely applied in river systems to assess flood impacts (Izumida et al., 2017), monitor bank erosion and channel dynamics (Hemmelder et al., 2018), and evaluate restoration outcomes (Marteau et al., 2017; Langhammer, 2019). By comparing multi-temporal DEMs or point clouds, practitioners can generate spatially explicit estimates of change, supporting process-based assessment of river behaviour. However, the reliability of these analyses depends on consistent data acquisition and careful management of uncertainty.

### 6.5.5 Cross-Section and Longitudinal Profile Analysis

UAV-derived point clouds and DEMs enable the extraction of channel cross-sections and longitudinal profiles for morphological and hydraulic analysis. These methods support detailed assessment of channel geometry and sediment distribution and have been used to quantify bank movement and channel adjustment (Hamshaw et al., 2017). Such analyses provide valuable inputs to hydraulic models and enable repeatable monitoring of channel change over time.

### 6.5.6 Spectral Indices and Image-Based Analysis

Multispectral UAV data enable the calculation of spectral indices for assessing vegetation and water characteristics. These approaches have been used to detect aquatic vegetation (Song and Park, 2020) and to characterise riparian structure and condition (Tomsett and Leyland, 2021). Spectral indices support quantitative ecological assessment and can be integrated with classification workflows to map habitat types and monitor vegetation change. However, their performance is dependent on sensor calibration and environmental conditions.

### 6.5.7 Velocimetry

UAV-based image velocimetry provides a non-intrusive method for estimating surface flow velocities, using techniques such as LSPIV and STIV (Manfreda et al., 2024; Pizarro et al., 2024). These methods have been successfully applied to measure surface velocities in river systems (Koutalakis et al., 2019; Tauro et al., 2016). UAV-based velocimetry offers a safer alternative to traditional in-channel measurements and can produce velocity fields at high spatial resolution. However, its application is dependent on visible tracers and suitable lighting conditions.

### 6.5.8 Image Classification and Habitat Mapping

Image classification techniques enable the mapping of land cover and habitat types from UAV datasets. These approaches have been applied to riparian zone classification (Michez et al., 2013) and long-term restoration monitoring (Langhammer, 2019). The integration of spectral and structural data, including canopy height models derived from LiDAR or SfM, improves classification accuracy. However, performance is influenced by shadowing, mixed pixels, and the availability of representative training data (Langhammer, 2019).

*Table 6-4: Summary of UAV data processing techniques for river restoration monitoring*

| Technique | Objective | Key Advantages | Key Limitations | Example Applications (Refs) | Software |
|---|---|---|---|---|---|
| **Site imagery** | Capture aerial imagery for site reconnaissance, documentation, and visual comparison | Rapid acquisition; minimal processing; intuitive outputs; useful for stakeholder engagement | Limited quantitative value without georeferencing; lower positional accuracy; restricted analytical capability | Site mapping and visual assessment (Rusnák et al., 2018) | Standard UAV software, GIS |
| **Orthophoto generation** | Produce georeferenced, distortion-free imagery for mapping, measurement, and classification | Full site coverage; high spatial resolution; compatible with RGB and multispectral data; relatively low cost | Surface-only information; dependent on lighting conditions; requires accurate georeferencing | Geomorphic mapping (Woodget et al., 2017); restoration monitoring (Langhammer et al., 2023) | ArcGIS, QGIS, Pix4D, Agisoft Metashape |
| **Point cloud generation (SfM)** | Create dense 3D point clouds from overlapping imagery for terrain reconstruction | Low-cost vs LiDAR; high resolution; retains colour information; widely accessible | Cannot penetrate vegetation; sensitive to image quality and terrain texture; computationally intensive | Glacial stream monitoring (Backes et al., 2020); geomorphic change (Evans et al., 2022) | Agisoft Metashape, Pix4D, CloudCompare |
| **DEM generation (SfM / LiDAR)** | Generate terrain models for morphological and hydraulic analysis | Enables quantitative terrain analysis; supports modelling; LiDAR captures vegetation structure | SfM limited in vegetated areas; LiDAR expensive; large data volumes | Terrain modelling (Javernick et al., 2014); hydrodynamic modelling (Langhammer et al., 2017); vegetation structure (Dufour et al., 2013) | ArcGIS, QGIS, CloudCompare |
| **Change detection (DoD / cloud differencing)** | Quantify spatial changes such as erosion and deposition through multi-temporal comparison | Provides quantitative evidence of change; high spatial resolution; supports process understanding | Sensitive to georeferencing errors; requires consistent acquisition; vegetation can introduce noise | Flood impacts (Izumida et al., 2017); bank erosion (Hemmelder et al., 2018); restoration assessment (Marteau et al., 2017; Langhammer, 2019) | ArcGIS, QGIS, CloudCompare |
| **Cross-section & long profile analysis** | Extract channel geometry for morphological assessment and hydraulic modelling | Rapid and repeatable; captures fine-scale topography; supports modelling workflows | Vegetation may obscure bed; DEM resolution limits small features; may require ground validation | Channel change and bank movement (Hamshaw et al., 2017) | ArcGIS, QGIS, CloudCompare, Excel |
| **Spectral indices calculation** | Quantify vegetation and water characteristics using band-based indices | Enables quantitative ecological assessment; | Requires calibration; sensitive to lighting and | Aquatic vegetation detection (Song and Park, 2020); | ArcGIS, QGIS, ENVI |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  |  | supports automated analysis; scalable | environmental conditions; dependent on sensor quality | vegetation structure mapping (Tomsett and Leyland, 2021) |  |
| **Velocimetry (LSPIV / STIV / PTV)** | Estimate surface flow velocities from image sequences | Non-intrusive; safer than in-channel methods; comparable accuracy to traditional approaches | Requires visible tracers; sensitive to lighting; limited to surface flow; requires high frame rates | Surface velocity measurement (Koutalakis et al., 2019; Tauro et al., 2016) | PIVlab, PTVlab, KU-STIV |
| **Image classification** | Classify land cover and habitat types to support restoration monitoring | Quantifies habitat extent; scalable; integrates spectral and structural data; supports automation | Requires training data; affected by shadows and mixed pixels; accuracy varies with conditions | Riparian classification (Michez et al., 2013); restoration monitoring (Langhammer, 2019) | ArcGIS, QGIS, ENVI |
| **Shade calculation** | Quantify shading across river reaches to assess thermal and ecological conditions | Provides quantitative measure of shading; supports habitat assessment and management planning | Time-specific outputs; requires multiple datasets for seasonal representation; processing can be intensive | Riparian shading analysis (Loicq et al., 2018) | ArcGIS |

## 6.6 Applications

Table 6-5 provides a practical mapping between UAV-based approaches and the monitoring domains defined within PRAGMO. The aim is not to restate conceptual principles, but to support rapid identification of where UAVs can be applied, what they can deliver, and how they align with existing guidance.

The table is intended as a lookup tool to support method selection during project design and monitoring planning. Users should begin with their monitoring objective and use the table to identify suitable UAV-based approaches and associated outputs.

It is important to note that many UAV datasets are multi-purpose. A single survey may support several monitoring objectives (e.g. morphology, vegetation, and floodplain connectivity), and should therefore be planned with this integration in mind. Conversely, UAV methods are not universally appropriate; their use should be considered alongside site conditions, data requirements, and the need for complementary field measurements.

*Table 6-5: PRAGMO × UAV Applications Matrix: mapping UAV capabilities to PRAGMO monitoring domains, indicators, and methods.*

| PRAGMO Domain | Monitoring Objective | UAV Capability | Recommended Sensors | Derived Metrics / Outputs | When to Apply | PRAGMO Linkage* | Example Applications (Refs) |
|---|---|---|---|---|---|---|---|
| **SMART Objectives & Design** | Define baseline, targets, and monitoring strategy | Rapid site mapping; repeatable surveys; scenario visualisation | RGB; LiDAR | Orthomosaics; DEMs; baseline condition maps | Pre + Post | Appendix 4 – SMART Objectives | Langhammer (2019); Woodget et al. (2017) |
| **Morphology** | Quantify channel form, structure, and complexity | High-resolution terrain modelling; spatial mapping | RGB; LiDAR (NIR/green) | Sinuosity; width; cross-sections; long profiles; geomorphic units | Pre + Post | Chapter 5 – Catchment Understanding; Appendix 12 – Hydromorphology; Appendix 13 – Hydromorphology | Backes et al. (2020); Woodget et al. (2017); Dietrich (2016) |
| **Sediment Dynamics** | Quantify erosion, deposition, and channel adjustment | Multi-temporal DEM differencing (DoD) | RGB; LiDAR | Elevation change; sediment budgets; planform change | Post (repeat surveys) | Chapter 5 – Catchment Understanding; Appendix 7 – Sedimentation | Izumida et al. (2017); Hemmelder et al. (2018) |
| **Hydrodynamics** | Measure flow characteristics and hydraulic behaviour | Image velocimetry; terrain-driven modelling | RGB (video); multispectral; LiDAR | Velocity fields; water level; discharge estimates | Pre + Post; events | Chapter 5 – Catchment Understanding; Appendix 5 – Hydrology | Koutalakis et al. (2019); Tauro et al. (2016); Langhammer et al. (2017) |
| **Vegetation & Habitat** | Assess riparian and aquatic vegetation extent and structure | Spectral mapping; 3D vegetation modelling | Multispectral; RGB; LiDAR | NDVI/NDWI; habitat classification; canopy height | Pre + Post | Appendix 11 – Vegetation Surveys | Dufour et al. (2013); Song and Park (2020); Tomsett and Leyland (2021) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Woody Material & Habitat Features** | Map large wood and habitat complexity | Feature extraction from orthos and point clouds | RGB; LiDAR | Woody debris distribution; structural complexity | Pre + Post | Appendix 11 – Vegetation Surveys; Appendix 12 – Hydromorphology | Kasprak et al. (2012); Langhammer et al. (2023) |
| **Floodplain Functionality** | Assess connectivity and inundation dynamics | DEM-based inundation modelling; event mapping | RGB; multispectral; LiDAR | Inundation extent; connectivity metrics | Post (events) | Appendix 12 – Hydromorphology; Appendix 13 – Hydromorphology | Izumida et al. (2017); Langhammer et al. (2017) |
| **Water Quality & Thermal Regime** | Identify temperature patterns and visible water quality indicators | Thermal mapping; spectral analysis | Thermal; multispectral | Temperature maps; turbidity proxies; pollution indicators | Pre + Post | Chapter 5 – Catchment Understanding; Appendix 6 – Water Quality | Manfreda et al. (2018); Song and Park (2020) |
| **Restoration Monitoring** | Evaluate restoration success and trajectory | Repeatable multi-sensor surveys; change detection | RGB; LiDAR; multispectral | Morphological change; vegetation recovery | Post (long-term) | Chapter 6 – Monitoring Objectives; Chapter 8 – Monitoring Timescales | Langhammer (2019); Evans et al. (2022) |
| **Stakeholder Engagement** | Communicate outcomes and support decisions | Visualisation and 3D modelling | RGB | Orthophotos; fly-throughs; 3D models | Pre + Post | Appendix 8 – Photography and Videography | Rusnák et al. (2018) |

**PRAGMO linkages are provided at the level of chapters and appendices to reflect the structure of the PRAGMO wiki. UAV applications often span multiple domains, particularly hydromorphology, hydrology, and vegetation monitoring.*

### 6.6.1 Selected Examples of UAV Use

*Table 6-6: Studies using UAVs to derive real-world measurements and metrics.*

| Paper | Use | Sensors used | Open Access? | DOI |
|---|---|---|---|---|
| Backes et al. (2020) | Glacial stream morphology | RGB | Yes | https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1017-2020 |
| Dufour et al. (2013) | 3D vegetation characterisation | LiDAR; RGB | Yes | https://doi.org/10.1051/kmae/2013068 |
| Evans et al. (2022) | Pre-/post-dam removal monitoring | RGB | Yes | https://doi.org/10.3390/drones6050100 |
| Izumida et al. (2017) | Floodplain geomorphic change | RGB | Yes | https://doi.org/10.5194/nhess-17-1505-2017 |
| Koutalakis et al. (2019) | Surface water velocity | RGB | Yes | https://doi.org/10.3390/drones3010014 |
| Langhammer et al. (2017) | Hydrodynamic flood modelling | RGB | Yes | https://doi.org/10.3390/w9110861 |
| Langhammer et al. (2023) | Restoration monitoring | RGB | Yes | https://doi.org/10.3390/hydrology10020048 |
| Langhammer (2019) | Long-term monitoring | RGB | Yes | https://doi.org/10.3390/hydrology6020029 |
| Song & Park (2020) | Aquatic plant detection | Multispectral | Yes | https://doi.org/10.3390/rs12030387 |
| Tomsett & Leyland (2023) | Terrain & vegetation structure | LiDAR; Multispectral | Yes | https://doi.org/10.5194/esurf-11-1223-2023 |
| Woodget et al. (2017) | Geomorphological mapping | RGB | Yes | https://doi.org/10.1002/wat2.1222 |
| Abalharth et al. (2015) | Logjam characterisation | LiDAR | No | https://doi.org/10.1016/j.geomorph.2015.06.036 |
| Dietrich (2016) | Riverscape mapping | RGB | No | https://doi.org/10.1016/j.geomorph.2015.05.008 |
| Dietrich (2017) | Bathymetry reconstruction | RGB | No | https://doi.org/10.1002/esp.4060 |
| Fleming (2025) | Palaeolandscape reconstruction | LiDAR; RGB | No | https://doi.org/10.1002/rra.4382 |
| Hamshaw et al. (2017) | Bank movement / topography | RGB | No | https://doi.org/10.1002/rra.3183 |
| Hemmelder et al. (2018) | Morphology & erosion | RGB | No | https://doi.org/10.1016/j.jag.2018.07.016 |
| Javernick et al. (2014) | Terrain modelling | RGB | No | https://doi.org/10.1016/j.geomorph.2014.01.006 |
| Kasprak et al. (2012) | LWD sources | LiDAR | No | https://doi.org/10.1002/rra.1532 |
| Kinzel et al. (2013) | Bathymetry mapping | LiDAR | No | https://doi.org/10.1111/jawr.12008 |
| Loicq et al. (2018) | Riparian shading | LiDAR | No | https://doi.org/10.1016/j.scitotenv.2017.12.129 |

| | | | | |
|---|---|---|---|---|
| Marteau et al. (2017) | Restoration geomorphology | RGB | No | https://doi.org/10.1002/esp.4086 |
| Michez et al. (2013) | Riparian classification | LiDAR | No | https://doi.org/10.1016/j.ecolind.2013.06.024 |
| Rusnák et al. (2018) | Riverscape mapping | RGB | No | https://doi.org/10.1016/j.measurement.2017.10.023 |
| Sarkar & Sinha (2025) | Geomorphic analysis | RGB | No | https://doi.org/10.1002/rra.4371 |
| Tauro et al. (2016) | Surface velocity | RGB | No | https://doi.org/10.1002/hyp.10698 |
| Woodget & Austrums (2017) | Grain size measurement | RGB | No | https://doi.org/10.1002/esp.4139 |

# 7 Detailed Case studies

## 7.1 River Itchen (Winchester) – Shading and Water Temperature

### 7.1.1 Site Overview

This case study focuses on a 500 m reach of the River Itchen as it flows through Winchester. The study reach comprises a multi-channel system, including a smaller western branch and a larger, more sinuous eastern channel (Figure X).

The site is characterised by a heterogeneous riparian corridor, including short grasses, shrubs, and mature trees, resulting in spatially variable shading conditions. Channel management includes routine weed cutting and maintenance of bank-side vegetation, producing a dynamic interaction between open and shaded channel sections. This variability provides an ideal setting for assessing the influence of riparian vegetation on in-channel thermal regimes.

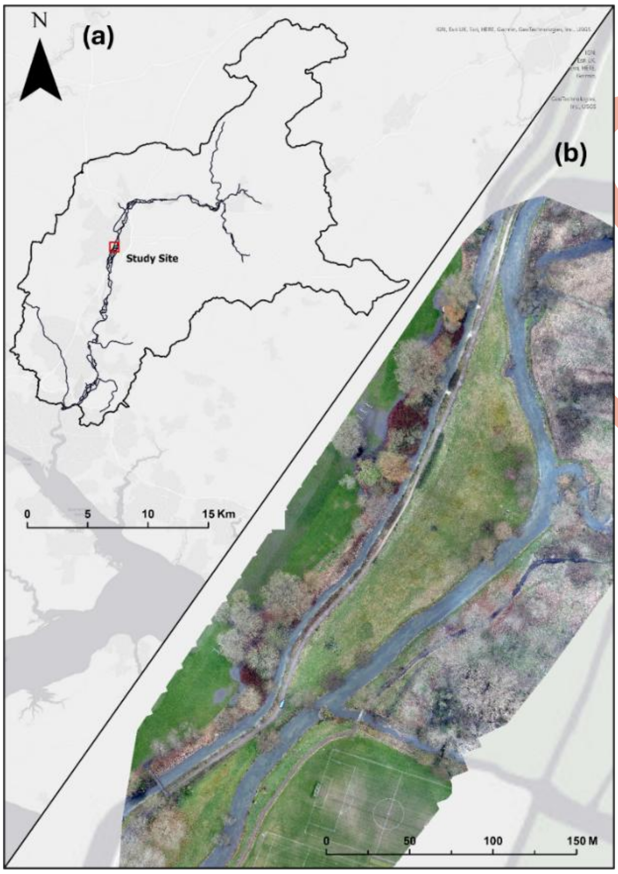


*Figure 5 Overview of the study site for the Itchen, with the wider catchment (top left) and study area (bottom right).*

### 7.1.2 Monitoring Objective

The objective of this case study was to quantify the spatial distribution of riparian shading and its influence on in-channel water temperature. Specifically, the study aimed to:

- *characterise vegetation structure and canopy extent along the river corridor,*
- *model spatial and temporal patterns of shading, and*

- *assess associated variability in surface water temperature.*

These outputs are directly relevant to river restoration, where riparian vegetation management (e.g. tree planting or clearance) is often used to regulate thermal regimes and improve habitat suitability for temperature-sensitive species.

### 7.1.3 Data Collection

Data were acquired using a DJI Matrice 300 RTK equipped with a multi-sensor payload comprising:

- *a UAV-mounted LiDAR system (Topodrone 100)*
- *an RGB camera (DJI Zenmuse P1)*
- *a thermal sensor (DJI Zenmuse H20T)*

RGB imagery was collected at approximately 2 cm ground sampling distance (GSD), while LiDAR data were acquired at a density of ~300 points $m^{-2}$. Thermal imagery was collected at coarser resolution, sufficient to resolve spatial variability in surface temperature.

Flights were conducted using a cross-grid survey pattern with terrain-following enabled, ensuring consistent spatial resolution across the study area. Each dataset required approximately 10 minutes of flight time per sensor.

Georeferencing was achieved using PPK workflows, supported by a network of Ground Control Points (GCPs) for validation and refinement. While PPK was applied in this instance, an RTK workflow implemented consistently across sensors would provide comparable positional accuracy.

### 7.1.4 Data Processing and Analysis

RGB and thermal imagery were processed in Pix4D Mapper to generate a high-resolution orthomosaic (2 cm), suitable for classification and spatial analysis. Thermal imagery was radiometrically calibrated using an open-source workflow based on the DJI SDK to improve comparability across the scene.

LiDAR data were processed using manufacturer software to produce a georeferenced point cloud, which was subsequently cropped and filtered within CloudCompare to isolate the study area. Ground and non-ground returns were separated using cloth simulation filtering, enabling the generation of a Digital Terrain Model (DTM) and Digital Surface Model (DSM).

A canopy height model (CHM) was derived by subtracting the DTM from the DSM, providing a spatial representation of vegetation height (Figure X). This CHM was combined with RGB imagery to produce a coarse land cover classification, distinguishing grasses, paths, shrubs, trees, and water.

Trees were extracted from this classification, with a minimum canopy threshold of 4 $m^2$ applied to reduce misclassification and ensure that only vegetation capable of influencing shading was included. While this threshold is pragmatic, it reflects a balance between classification robustness and ecological relevance.

Shading extent was modelled using canopy height and position in conjunction with the LiDAR-derived terrain surface. Simulations were conducted for multiple times of day (e.g. 10:00, 13:00, and 16:00) and across contrasting seasonal conditions (e.g. spring and autumn), representing variations in solar angle and canopy state. The resulting outputs were combined to produce spatially explicit maps of shading frequency across the river corridor.

Thermal imagery was clipped to the active channel extent, defined using the classification outputs. This ensured that analysis was restricted to water surface temperatures, removing interference from adjacent vegetation or bank surfaces.

### 7.1.5 Key Outputs

The workflow produced a suite of spatial datasets directly relevant to restoration monitoring, including:

- *high-resolution orthomosaics for site mapping and classification*
- *LiDAR-derived terrain (DTM) and surface (DSM) models*
- *canopy height models (CHM) representing vegetation structure*
- *classified land cover maps of the river corridor*
- *spatially explicit shading models for multiple times and seasons*
- *channel-constrained thermal imagery representing surface water temperature*

Together, these outputs provide an integrated representation of the relationships between vegetation structure, shading, and thermal variability.

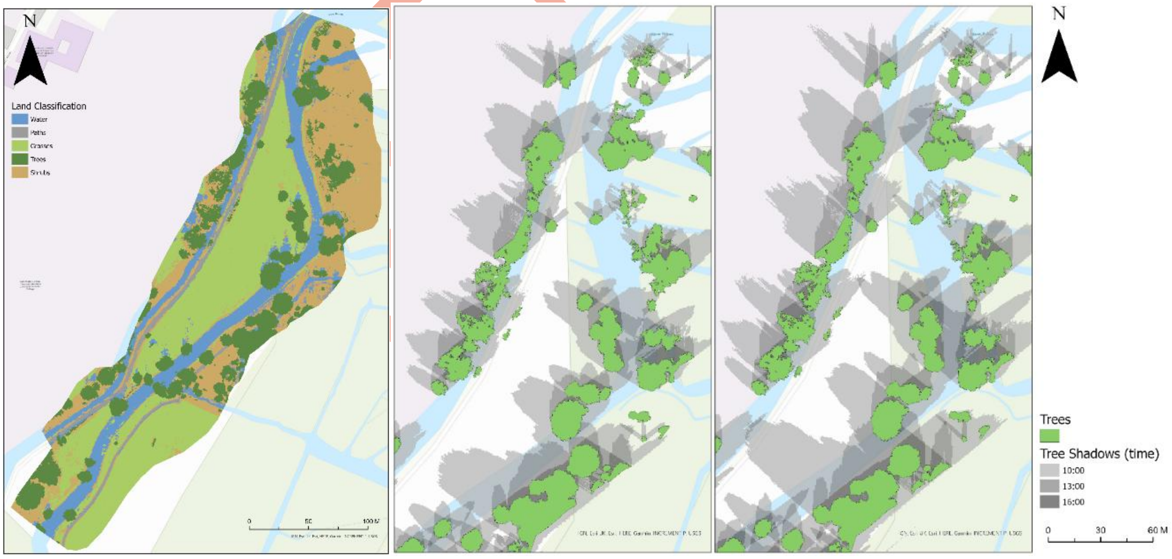


*Figure 6: (Left) Land cover classification map of the study site. Canopy shading maps at 10:00, 13:00, and 16:00 on 01/04/25 (centre) and 01/10/25 (right). Green polygons indicate tree cover greater than 4 m$^2$.*

### 7.1.6 Implications for Practitioners

This case study demonstrates how UAV-based workflows can be used to quantify riparian shading and its influence on thermal regimes within river systems. For practitioners, this provides a direct means of linking vegetation structure to habitat conditions, supporting both restoration planning and evaluation.

The approach enables baseline assessment of shading conditions prior to intervention, allowing areas of insufficient or excessive shading to be identified. It also supports scenario-based analysis, where different planting or management strategies can be evaluated in terms of their likely impact on shading patterns.

Repeat surveys allow changes in vegetation structure and shading to be tracked over time, providing a basis for assessing restoration outcomes and supporting adaptive management. The integration of thermal imagery further enhances this capability by enabling spatial patterns of temperature variability to be assessed, including the identification of potential thermal refugia.

While this case study utilises high-specification UAV and LiDAR systems, similar workflows can be adapted using lower-cost platforms and open-access datasets. For example, airborne LiDAR datasets may provide a baseline for canopy modelling, although these are typically temporally constrained and may lack the resolution required for fine-scale analysis (see Section X.X).

Overall, UAV-based approaches provide a flexible and scalable method for integrating shading and thermal monitoring within river restoration projects, supporting more quantitative, evidence-based assessment of ecological outcomes.

***Figure 7:*** *A section of the study site at different scales, with images captured on the DJI Mavic* ***(left)*** *and DJI Matrice* ***(right)****.*

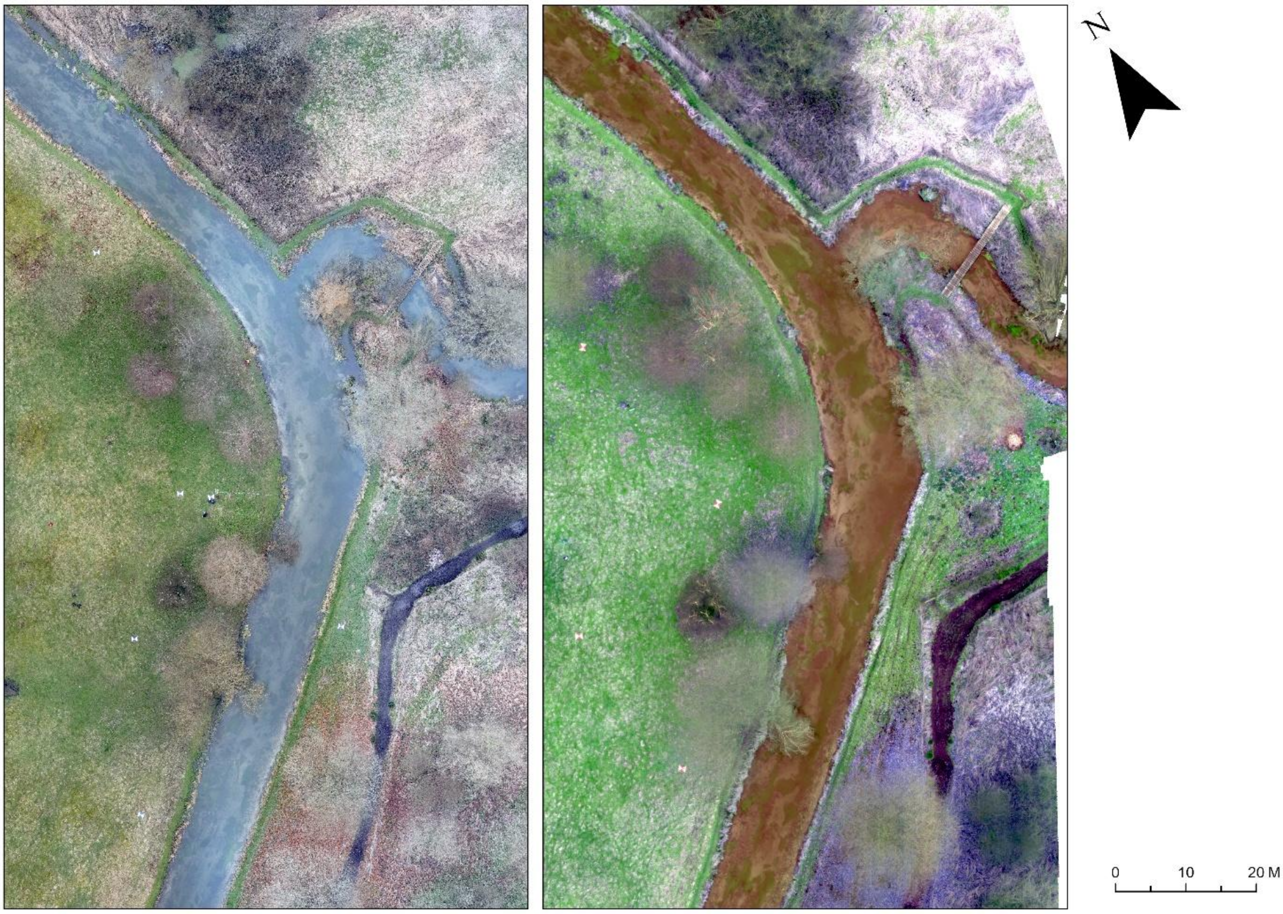


***Figure 8:** A section of the orthomosaic images of the study iin RGB **(left)** and red-edge imagery **(right)**.*

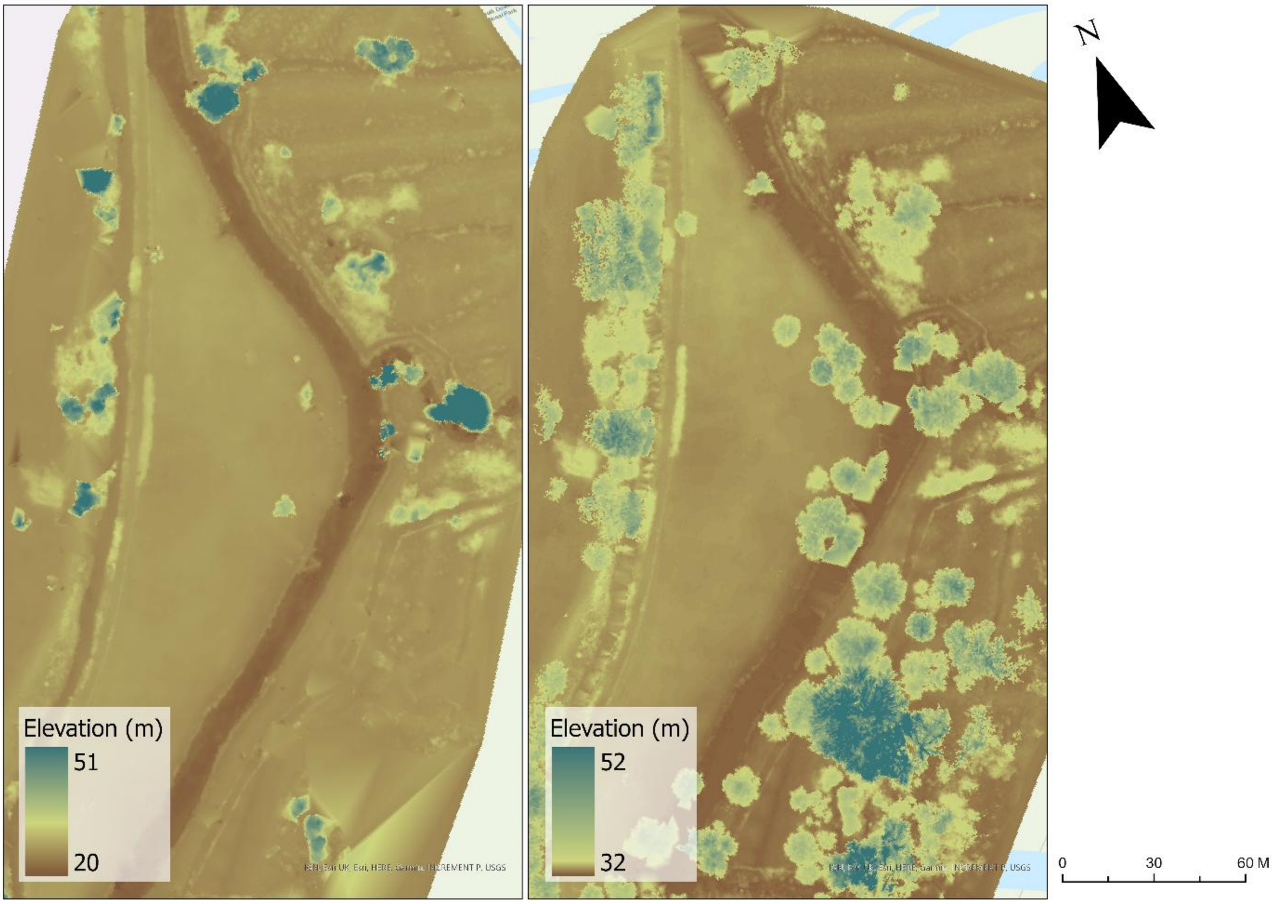


*Figure 9: DEMs created using point cloud data generated by SfM (left) and LiDAR (right).*

## 7.2 River Stiffkey (Norfolk) – Morphological Baselining

### 7.2.1 Site Overview

This case study focuses on a restored reach of the River Stiffkey in Norfolk, managed by the Norfolk Rivers Trust. The site forms part of a larger restoration programme aimed at re-establishing natural channel processes and improving habitat diversity.

Prior to restoration, the channel had been historically straightened, a common modification across UK lowland rivers. Restoration works included re-meandering the channel and the strategic placement of large woody material to increase hydraulic roughness, promote sediment retention, and enhance habitat heterogeneity.

UAV surveying was undertaken immediately following restoration, providing a high-resolution morphological baseline against which future channel adjustment and habitat development can be assessed.

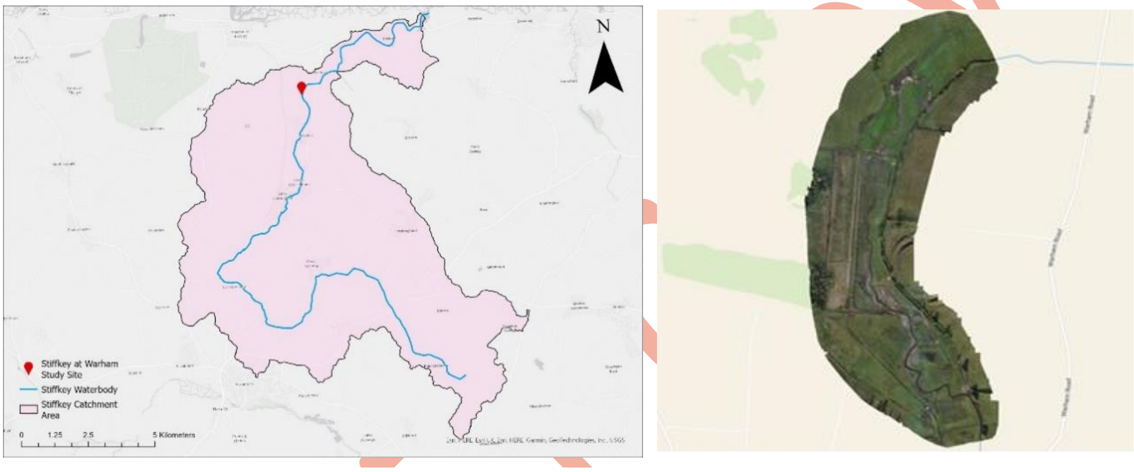


*Figure 10 Location overview of the River Stiffkey, showing the river catchment and study site location within this (left), as well as an orthomosaic of the field site collected form UAV imagery.*

### 7.2.2 Monitoring Objective

The objective of this case study was to establish a quantitative morphological baseline for a recently restored river reach. Specifically, the study aimed to:

- *characterise channel form and bed topography at high spatial resolution*
- *map the distribution and structure of riparian vegetation and woody material*
- *develop datasets suitable for long-term monitoring of geomorphic change and restoration outcomes.*

These outputs are directly aligned with PRAGMO objectives, supporting the evaluation of restoration success through measurable indicators of channel adjustment and habitat development.

### 7.2.3 Data Collection

Data were acquired in November 2023 using a DJI Matrice 300 RTK equipped with:

- *a UAV-mounted LiDAR system (Topodrone 100)*
- *an RGB camera (DJI Zenmuse P1)*

RGB imagery was collected at high spatial resolution (cm-scale), while LiDAR data were acquired at a density of approximately 300 points m$^{-2}$. Surveys were conducted using a cross-grid flight pattern with terrain-following enabled to ensure consistent ground sampling distance (GSD). To comply with UK Civil Aviation Authority (CAA) visual line-of-sight (VLOS) regulations, the study reach was divided into northern and southern survey segments. Georeferencing was achieved using PPK workflows, supported by a network of Ground Control Points (GCPs). In addition, a GNSS RTK system was used to collect cross-sectional data along the channel, providing independent, high-accuracy validation of UAV-derived elevation models.

### 7.2.4 Data Processing and Analysis

RGB imagery was processed in Pix4D Mapper to generate an orthomosaic and a photogrammetric point cloud. LiDAR data were processed using manufacturer software to produce a fully georeferenced point cloud, which was subsequently cropped and filtered within CloudCompare.

Ground and non-ground returns were separated using cloth simulation filtering, enabling the generation of Digital Terrain Models (DTMs) and Digital Surface Models (DSMs). A canopy height model (CHM) was derived by subtracting the DTM from the DSM, providing a representation of vegetation structure across the site.

These datasets were integrated to support a series of analytical workflows, including:

- ***Cross-section analysis**: GNSS and SfM-derived elevation profiles were compared to assess channel geometry and validate UAV-derived terrain models. Cross-sections were extracted and analysed to quantify channel form and hydraulic capacity.*
- ***Woody debris mapping**: Orthomosaic imagery was used to digitise and quantify large woody material within the channel, enabling future monitoring of accumulation and redistribution.*
- ***Vegetation structure analysis**: LiDAR point clouds were segmented to characterise three-dimensional vegetation structure and support classification workflows.*
- ***Land classification**: A composite dataset combining orthomosaic imagery, CHM, and LiDAR-derived rasters was used to classify land cover into categories such as bare ground, vegetation, shrubs, and water. Multiple classification algorithms were tested, with Random Tree providing the most robust results.*

To extend analysis into the channel, through-water Structure-from-Motion (SfM) techniques were applied to estimate bed elevations. Water surface levels were identified using combined imagery and LiDAR point density, and depth corrections were applied using a refraction coefficient (~1.34). These results were validated against GNSS-derived cross-sections.

### 7.2.5 Key Outputs

The workflow produced a comprehensive suite of datasets for baseline assessment and long-term monitoring, including:

- *high-resolution orthomosaics of the restored reach*
- *LiDAR-derived DTMs, DSMs, and canopy height models*
- *cross-sectional profiles derived from both GNSS and SfM data*
- *shapefiles of cross-section locations and woody debris distribution*
- *classified land cover maps using multiple classification approaches*
- *bathymetric estimates derived from through-water SfM*

These outputs provide a detailed, spatially explicit representation of channel morphology, vegetation structure, and restoration impacts.

### 7.2.6 Implications for Practitioners

This case study demonstrates the value of UAV-based surveying for establishing high-resolution morphological baselines immediately following restoration. Such datasets provide a critical reference point against which future channel adjustment, sediment dynamics, and habitat development can be quantitatively assessed. The integration of UAV-derived data with GNSS measurements represents a significant advancement over traditional monitoring approaches, which often rely on sparse cross-sections or longitudinal profiles. By capturing continuous spatial data across the entire reach, practitioners can move towards more comprehensive and process-based assessment of restoration outcomes.

The ability to map and monitor woody material provides additional insight into habitat complexity and hydraulic behaviour, including the influence of large wood on sediment deposition and channel form. Similarly, land classification outputs allow the recovery of disturbed areas (e.g. bare ground following construction) to be tracked over time, supporting assessment of ecological recovery and alignment with broader objectives such as biodiversity net gain. The use of LiDAR is particularly valuable in vegetated environments, enabling continued monitoring as riparian vegetation develops. This supports not only geomorphic analysis but also the assessment of vegetation structure, biomass, and potential carbon storage.

While the approach presented here utilises high-specification UAV systems, elements of the workflow can be adapted to lower-cost platforms or combined with existing datasets. However, the accuracy and completeness of the resulting products will depend on sensor capability and survey design. Overall, UAV-based approaches provide a robust and scalable framework for baseline characterisation and long-term monitoring, supporting more quantitative and evidence-based evaluation of river restoration within a PRAGMO context.

Figures??

Figure X: Cross-section comparisons (GNSS vs SfM)

Figure X: Land classification outputs (multiple classifiers)

Figure X: Woody debris mapping

## 7.3 River Test – All things fishy

### 7.3.1 Site overview

### 7.3.2 Data collection

### 7.3.3 Data processing

### 7.3.4 Implications for practitioners

## 7.4 Avon Water – Paleo Channel Extraction

### 7.4.1 Site overview

### 7.4.2 Data collection

### 7.4.3 Data processing

### 7.4.4 Implications for practitioners

# 8 Glossary of Common Terms and Acronyms

Below is non-comprehensive list of acronyms one might come across when undertaking UAV-based surveying for river restoration and beyond. Not all terms used within UAV deployments will be noted below, however all used within this document are listed here.

| Acronym | Term | Definition |
|---|---|---|
| DTM | Digital Terrain Model | A representation of the Earth's surface without and features such as trees or building present. Sometimes known as a bare-earth model. |
| GCP | Ground Control Point | A 1 m x 1 m marker which is placed on the ground and surveyed using GNSS to provide a network of georeferenced points visible in aerial images. |
| GNSS | Global Navigation Satellite System | The standard generic term for satellite navigation systems that provide geospatial positioning with global coverage (e.g. GPS, GLONASS, GALILEO). |
| GPS | Global Positioning System | The US administered satellite navigation system. Often used as an alternative to GNSS, but technically only refers to the specific system. |
| INS | Inertial Navigation System | A navigation device that uses motion and rotation sensors to continuously calculate by dead reckoning the position, orientation, and velocity of a moving object without the need for external references. |
| LiDAR | Light Detection And Ranging | A remote sensing method using light in the form of a pulsed or continuous waveform laser to measure distances to ground targets. |
| MSL | Mean Sea Level | An average level of the surface of a body of water from which heights such as elevation may be measured. |
| NOPK | No Positional Kinematic | In the absence of RTK or PPK, i.e. positional quality is relatively low |
| NTRIP | Networked Transport of RTCM via Internet Protocol | Protocol for streaming differential GNSS data over the Internet. |
| ODN | Ordnance Datum Newlyn | The vertical reference frame used throughout the UK to describe height above mean sea level. |
| OSGB | Ordnance Survey Great Britain | The Ordnance Survey National Grid is a system of geographic grid references used in Great Britain. |
| OSTN15 | Ordnance Survey National Grid Transformation 2015 | The national standard transformation for transforming GNSS coordinates to OSGB36 National Grid coordinates, and vice-versa. |
| PPK | Post Processed Kinematic | Position location process whereby signals received from a mobile location receiving device can be adjusted using corrections from a reference Station after data collection has completed. |
| RINEX | Receiver Independent Exchange Format | A data interchange format for raw satellite navigation system data. |

| | | |
|---|---|---|
| RTK | Real Time Kinematic | A satellite navigation technique used to enhance the precision of position data during a flight derived from satellite-based positioning systems. |
| UAV/UAS | Uncrewed Aerial Vehicle/ Uncrewed Aerial System | Commonly known as a drone, is an aircraft without any human pilot, crew, or passengers on board. |
| UTM | Universal Transverse Mercator | A system for assigning projected coordinates to locations on the surface of the Earth. |
| WGS 84 | World Geodetic System 1984 | A geographic coordinate reference system using degrees as its unit of measurement |
| DSM | Digital Surface Model | A representation of an areas surface, including features such as trees, buildings, and structures. |
| CHM | Canopy Height Model | A digital reconstruction that represents the height of vegetation across a study site. |

# 9 References

Abalharth, M., Hassan, M. A., Klinkenberg, B., Leung, V. and McCleary, R. (2015) 'Using LiDAR to characterize logjams in lowland rivers', *Geomorphology,* 246, pp. 531-541. https://doi.org/10.1016/j.geomorph.2015.06.036

Acharya, B. S., Bhandari, M., Bandini, F., Pizarro, A., Perks, M., Joshi, D. R., Wang, S., Dogwiler, T., Ray, R. L., Kharel, G. and Sharma, S. (2021) 'Unmanned Aerial Vehicles in Hydrology and Water Management: Applications, Challenges, and Perspectives', *Water Resources Research,* 57(11). https://doi.org/10.1029/2021wr029925

Aicardi, I., Chiabrando, F., Lingua, A. M., Noardo, F., Piras, M. and Vigna, B. (2017) 'A methodology for acquisition and processing of thermal data acquired by UAVs: a test about subfluvial springs' investigations', *Geomatics, Natural Hazards and Risk,* 8(1), pp. 5-17. https://doi.org/10.1080/19475705.2016.1225229

Al-Zankana, A. F. A., Matheson, T. and Harper, D. M. (2020) 'How strong is the evidence – based on macroinvertebrate community responses – that river restoration works?', *Ecohydrology & Hydrobiology,* 20(2), pp. 196-214. https://doi.org/10.1016/j.ecohyd.2019.11.001

Backes, D., Smigaj, M., Schimka, M., Zahs, V., Grznárová, A. and Scaioni, M. (2020) 'River morphology monitoring of a small-scale alpine riverbed using drone photogrammetry and LiDAR', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 43, pp. 1017-1024. https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1017-2020

Cai, J., Meng, L., Liu, H., Chen, J. and Xing, Q. (2022) 'Estimating Chemical Oxygen Demand in estuarine urban rivers using unmanned aerial vehicle hyperspectral images', *Ecological Indicators,* 139, pp. 108936. https://doi.org/10.1016/j.ecolind.2022.108936

Carrivick, J. L. and Smith, M. W. (2019) 'Fluvial and aquatic applications of Structure from Motion photogrammetry and unmanned aerial vehicle/drone technology', *Wiley Interdisciplinary Reviews: Water,* 6(1), pp. e1328. https://doi.org/10.1002/wat2.1328

Colomina, I. and Molina, P. (2014) 'Unmanned aerial systems for photogrammetry and remote sensing: A review', *ISPRS Journal of Photogrammetry and Remote Sensing,* 92, pp. 79-97. https://doi.org/10.1016/j.isprsjprs.2014.02.013

Dietrich, J. T. (2016) 'Riverscape mapping with helicopter-based Structure-from-Motion photogrammetry', *Geomorphology,* 252, pp. 144-157. https://doi.org/10.1016/j.geomorph.2015.05.008

Dietrich, J. T. (2017) 'Bathymetric Structure-from-Motion: extracting shallow stream bathymetry from multi-view stereo photogrammetry', *Earth Surface Processes and Landforms,* 42(2), pp. 355-364. https://doi.org/10.1002/esp.4060

Dufour, S., Bernez, I., Betbeder, J., Corgne, S., Hubert-Moy, L., Nabucet, J., Rapinel, S., Sawtschuk, J. and Trollé, C. (2013) 'Monitoring restored riparian vegetation: how can recent developments in remote sensing sciences help?', *Knowledge and Management of Aquatic Ecosystems,* (410), pp. 10. https://doi.org/10.1051/kmae/2013068

England, J., Angelopoulos, N., Cooksley, S., Dodd, J., Gill, A., Gilvear, D., Johnson, M., Naura, M., O'Hare, M., Tree, A., Wheeldon, J. and Wilkes, M. A. (2021) 'Best Practices for Monitoring and Assessing the Ecological Response to River Restoration', *Water,* 13(23), pp. 3352. https://doi.org/10.3390/w13233352

Environment Agency, Scottish Environment Protection Agency (SEPA) and Environment and Heritage Service (2022) *River Habitat Survey in Britain and Ireland: Field Survey Guidance Manual: 2003 version*, Bristol, UK: Environment Agency.

Evans, A. D., Gardner, K. H., Greenwood, S. and Still, B. (2022) 'UAV and structure-from-motion photogrammetry enhance river restoration monitoring: A dam removal study', *Drones,* 6(5), pp. 100. https://doi.org/10.3390/drones6050100

Fleming, E. (2025) 'Unveiling Stage Zero Conditions in the New Forest National Park: A UAV-Based Structure-From-Motion Photogrammetry and LiDAR Approach for Reconstructing an Anastomosing Wet Woodland at the Avon Water', *River Research and Applications,* 41(1), pp. 159-176. https://doi.org/10.1002/rra.4382

Hackney, C. and Clayton, A. (2015) '2.1.7. Unmanned Aerial Vehicles (UAVs) and their application in geomorphic mapping', in Clarke, L. and Nield, J.M. (eds.) *Geomorphological Techniques*. London, GB: British Society of Geomorphology.

Hamshaw, S. D., Bryce, T., Rizzo, D. M., O'Neil-Dunne, J., Frolik, J. and Dewoolkar, M. M. (2017) 'Quantifying streambank movement and topography using unmanned aircraft system photogrammetry with comparison to terrestrial laser scanning', *River Research and Applications,* 33(8), pp. 1354-1367. https://doi.org/10.1002/rra.3183

Hemmelder, S., Marra, W., Markies, H. and De Jong, S. M. (2018) 'Monitoring river morphology & bank erosion using UAV imagery–A case study of the river Buëch, Hautes-Alpes, France', *International Journal of Applied Earth Observation and Geoinformation,* 73, pp. 428-437. https://doi.org/10.1016/j.jag.2018.07.016

Izumida, A., Uchiyama, S. and Sugai, T. (2017) 'Application of UAV-SfM photogrammetry and aerial lidar to a disastrous flood: repeated topographic measurement of a newly formed crevasse splay of the Kinu River, central Japan', *Natural Hazards and Earth System Sciences,* 17(9), pp. 1505-1519. https://doi.org/10.5194/nhess-17-1505-2017

James, M.R., Robson, S. and Smith, M.W., 2017. '3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys'. *Earth Surface Processes and Landforms*, *42*(12), pp.1769-1788. https://doi.org/10.1002/esp.4125

James, M.R., Chandler, J.H., Eltner, A., Fraser, C., Miller, P.E., Mills, J.P., Noble, T., Robson, S. and Lane, S.N., 2019. 'Guidelines on the use of structure-from-motion photogrammetry in geomorphic research'. *Earth Surface Processes and Landforms*, *44*(10), pp.2081-2084. https://doi.org/10.1002/esp.4637

Javernick, L., Brasington, J. and Caruso, B. (2014) 'Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry', *Geomorphology,* 213, pp. 166-182. https://doi.org/10.1016/j.geomorph.2014.01.006

Kasprak, A., Magilligan, F. J., Nislow, K. H. and Snyder, N. P. (2012) 'A Lidar-Derived Evaluation of Watershed-Scale Large Woody Debris Sources and Recruitment Mechanisms: Coastal Maine, USA', *River Research and Applications,* 28(9), pp. 1462-1476. https://doi.org/10.1002/rra.1532

Kinzel, P. J., Legleiter, C. J. and Nelson, J. M. (2013) 'Mapping River Bathymetry With a Small Footprint Green LiDAR: Applications and Challenges', *JAWRA Journal of the American Water Resources Association,* 49(1), pp. 183-204. https://doi.org/10.1111/jawr.12008

Kinzel, P. J., Wright, C. W., Nelson, J. M. and Burman, A. R. (2007) 'Evaluation of an Experimental LiDAR for Surveying a Shallow, Braided, Sand-Bedded River', *Journal of Hydraulic*

*Engineering,* 133(7), pp. 838-842. https://doi.org/10.1061/(asce)0733-9429(2007)133:7(838)

Koutalakis, P., Tzoraki, O. and Zaimes, G. (2019) 'UAVs for Hydrologic Scopes: Application of a Low-Cost UAV to Estimate Surface Water Velocity by Using Three Different Image-Based Methods', *Drones,* 3(1), pp. 14. https://doi.org/10.3390/drones3010014

Langhammer, J. (2019) 'UAV monitoring of stream restorations', *Hydrology,* 6(2), pp. 29. https://doi.org/10.3390/hydrology6020029

Langhammer, J., Bernsteinová, J. and Miřijovský, J. (2017) 'Building a High-Precision 2D Hydrodynamic Flood Model Using UAV Photogrammetry and Sensor Network Monitoring', *Water,* 9(11), pp. 861. https://doi.org/10.3390/w9110861

Langhammer, J., Lendzioch, T. and Šolc, J. (2023) 'Use of UAV monitoring to identify factors limiting the sustainability of stream restoration projects', *Hydrology,* 10(2), pp. 48. https://doi.org/doi.org/10.3390/hydrology10020048

Liu, H., Yu, T., Hu, B., Hou, X., Zhang, Z., Liu, X., Liu, J., Wang, X., Zhong, J., Tan, Z., Xia, S. and Qian, B. (2021) 'UAV-Borne Hyperspectral Imaging Remote Sensing System Based on Acousto-Optic Tunable Filter for Water Quality Monitoring', *Remote Sensing,* 13(20), pp. 4069. https://doi.org/10.3390/rs13204069

Loicq, P., Moatar, F., Jullian, Y., Dugdale, S. J. and Hannah, D. M. (2018) 'Improving representation of riparian vegetation shading in a regional stream temperature model using LiDAR data', *Science of The Total Environment,* 624, pp. 480-490. https://doi.org/10.1016/j.scitotenv.2017.12.129

Manfreda, S., McCabe, M. F., Miller, P. E., Lucas, R., Pajuelo Madrigal, V., Mallinis, G., Ben Dor, E., Helman, D., Estes, L., Ciraolo, G., Müllerová, J., Tauro, F., De Lima, M. I., De Lima, J. L. M. P., Maltese, A., Frances, F., Caylor, K., Kohv, M., Perks, M., Ruiz-Pérez, G., Su, Z., Vico, G. and Toth, B. (2018) 'On the Use of Unmanned Aerial Systems for Environmental Monitoring', *Remote Sensing,* 10(4), pp. 641. https://doi.org/10.3390/rs10040641

Manfreda, S., Miglino, D., Saddi, K. C., Jomaa, S., Eltner, A., Perks, M., Peña-Haro, S., Bogaard, T., Van Emmerik, T. H. M., Mariani, S., Maddock, I., Tauro, F., Grimaldi, S., Zeng, Y., Gonçalves, G., Strelnikova, D., Bussettini, M., Marchetti, G., Lastoria, B., Su, Z. and Rode, M. (2024) 'Advancing river monitoring using image-based techniques: challenges and opportunities', *Hydrological Sciences Journal,* 69(6), pp. 657-677. https://doi.org/10.1080/02626667.2024.2333846

Marteau, B., Vericat, D., Gibbins, C., Batalla, R. J. and Green, D. R. (2017) 'Application of Structure-from-Motion photogrammetry to river restoration', *Earth Surface Processes and Landforms,* 42(3), pp. 503-515. https://doi.org/10.1002/esp.4086

Michez, A., Piégay, H., Toromanoff, F., Brogna, D., Bonnet, S., Lejeune, P. and Claessens, H. (2013) 'LiDAR derived ecological integrity indicators for riparian zones: Application to the Houille river in Southern Belgium/Northern France', *Ecological Indicators,* 34, pp. 627-640. https://doi.org/10.1016/j.ecolind.2013.06.024

Otto, J.-C. and Smith, M. (2013) 'Geomorphological Mapping', in Clarke, L. (ed.) *Geomorphological Techniques*: British Society for Geomorphology.

Peña-Haro, S., Carrel, M., Lüthi, B., Hansen, I. and Lukes, R. (2021) 'Robust Image-Based Streamflow Measurements for Real-Time Continuous Monitoring', *Frontiers in Water,* 3. https://doi.org/10.3389/frwa.2021.766918

Pizarro, A., Valera-Gran, D., Navarrete-Muñoz, E.-M. and Dal Sasso, S. F. (2024) 'The Use of Unmanned Aerial Systems for River Monitoring: A Bibliometric Analysis Covering the Last 25 Years', *Hydrology,* 11(6), pp. 80. https://doi.org/10.3390/hydrology11060080

Rusnák, M., Sládek, J., Kidová, A. and Lehotský, M. (2018) 'Template for high-resolution river landscape mapping using UAV technology', *Measurement,* 115, pp. 139-151. https://doi.org/10.1016/j.measurement.2017.10.023

Sarkar, D. and Sinha, R. (2025) 'Integrating UAV-Based Topographic and Geomorphic Analysis for the Development of River Rehabilitation Plans in Semi-Urban Settings', *River Research and Applications,* 41(2), pp. 314-333. https://doi.org/10.1002/rra.4371

Sear, D., Newson, M. and Thorne, C. (2003) *Guidebook of Applied Fluvial Geomorphology* [R&D Technical Report FD1914], London: Defra/Environment Agency.

Sedano-Cibrián, J., Pérez-Álvarez, R., De Luis-Ruiz, J. M., Pereda-García, R. and Salas-Menocal, B. R. (2022) 'Thermal Water Prospection with UAV, Low-Cost Sensors and GIS. Application to the Case of La Hermida', *Sensors,* 22(18), pp. 6756. https://doi.org/10.3390/s22186756

Song, B. and Park, K. (2020) 'Detection of Aquatic Plants Using Multispectral UAV Imagery and Vegetation Index', *Remote Sensing,* 12(3), pp. 387. https://doi.org/10.3390/rs12030387

Tauro, F., Petroselli, A. and Arcangeletti, E. (2016) 'Assessment of drone-based surface flow observations', *Hydrological Processes,* 30(7), pp. 1114-1130. https://doi.org/10.1002/hyp.10698

Tomsett, C. and Leyland, J. (2019) 'Remote sensing of river corridors: A review of current trends and future directions', *River Research and A pplications,* 35(7), pp. 779-803. https://doi.org/10.1002/rra.3479

Tomsett, C. and Leyland, J. (2021) 'Development and Testing of a UAV Laser Scanner and Multispectral Camera System for Eco-Geomorphic Applications', *Sensors,* 21(22), pp. 7719. https://doi.org/10.3390/s21227719s

Tomsett, C. and Leyland, J. (2023). 'Using repeat UAV-based laser scanning and multispectral imagery to explore eco-geomorphic feedbacks along a river corridor.' *Earth Surface Dynamics*, 11(6), 1223–124. https://doi.org/10.5194/esurf-11-1223-2023

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. and Reynolds, J. M. (2012) 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications', *Geomorphology,* 179, pp. 300-314. https://doi.org/10.1016/j.geomorph.2012.08.021

Woodget, A., Austrums, R., Maddock, I. and Habit, E. (2017) 'Drones and digital photogrammetry: from classifications to continuums for monitoring river habitat and hydromorphology', *Wiley Interdisciplinary Reviews: Water,* 4, pp. e1222. https://doi.org/10.1002/wat2.1222

Woodget, A. S. and Austrums, R. (2017) 'Subaerial gravel size measurement using topographic data derived from a UAV-SfM approach', *Earth Surface Processes and Landforms,* 42(9), pp. 1434-1443. https://doi.org/10.1002/esp.4139

Ye, N., Walker, J. P., Gao, Y., Popstefanija, I. and Hills, J. (2024) 'Comparison Between Thermal-Optical and L-Band Passive Microwave Soil Moisture Remote Sensing at Farm Scales: Towards UAV-Based Near-Surface Soil Moisture Mapping', *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* 17, pp. 633-642. https://doi.org/10.1109/jstars.2023.3329015

You, H. and Kim, D. (2021) 'Development of an Image Registration Technique for Fluvial Hyperspectral Imagery Using an Optical Flow Algorithm', *Sensors,* 21(7), pp. 2407. https://doi.org/10.3390/s21072407

Young, E. J. (2012) '2.1.3. dGPS', in Clarke, L. and Nield, J.M. (eds.) *Geomorphological Techniques*. London, GB: British Society of Geomorphology.