Article

UAV Monitoring of Stream Restorations

Jakub Langhammer *

Charles University, Faculty of Science, Department of Physical Geography and Geoecology, Albertov 6, 128 43 Prague 2, Czech Republic; jakub.langhammer@natur.cuni.cz; Tel.: +420-221-951-364

Abstract: This study examines the potential and limits of the unmanned aerial vehicles (UAVs) applicability for the monitoring of stream restoration in an urban environment. UAV imaging was used for long-term post-restoration monitoring of an urban stream. The monitoring was aimed to track the stream changes significant for the assessment of the restoration success, such as the compliance of the restoration to the plan, stability and evolution of the stream channel, or changes in stream and riparian habitats. The recurrent imaging campaigns in the restored segment of Hostavicky brook in Prague, The Czech Republic, were undertaken for three years since the restoration using the DJI Inspire 1 Pro platform. The UAV monitoring revealed that the new stream pattern substantially differs from the proposed restoration plan. Despite this, the new channel has proved stability, supported by intense grassing of the floodplain, resulting in only marginal evolution of the restored channel. The new channel proved the ability to mitigate the course of a significant flood event without significant flood spills outside the riparian zone. The UAV monitoring also revealed intense eutrophication in newly created shallow ponds with insufficient drainage. The research proved that UAV imaging is a unique source of spatial data, providing reliable information for quantitative and qualitative assessment of the stream restoration progress and success.

Keywords: rivers; restoration; ecohydrology; hydromorphology; UAV; monitoring

1. Introduction

Recent advances in the accessibility and quality of remote sensing data products accelerate the number of their applications in landscape studies, including water management. Remote sensing data represent an accurate and reliable tool for landscape planning, enabling objective assessment of the complex segments of the riverscape [1,2]. However, the broader use of satellite imagery in the stream restoration design and monitoring projects remains limited due to the coarse spatial resolution of the imagery [3]. The low spatial resolution of the imagery, however, limits applications of the satellite data to large rivers, where the potential of the multispectral and hyperspectral imagery is used mainly for classification of vegetation properties of the riverscape [4,5]. The substantial shift of the applicability of the remotely sensed data has been brought by the increasing availability of high-resolution aerial orthoimagery, allowing the distinction of basic hydromorphological properties of the physical stream habitat [6,7]. However, the orthoimagery products based on the airborne imagery still suffer from two substantial limitations. First, the imagery resolution, although continuously increasing, still does not allow the analysis of the physical habitat and structural properties of small streams, typical in the urban and suburban environment, that are the subjects of restoration. Second, and more important, is the limitation by low temporal resolution and poor operability of the survey. The typical interval for a geodetic survey is in years, while the monitoring of the stream restoration projects requires higher frequency and flexibility to capture the data on demand.

Unmanned aerial vehicles and systems (UAV, UAS, drones), as a rapidly evolving yet proven imaging technology, emerged and developed as a technique suitable to fill the needs of detailed

monitoring of the riverscape [8–10]. Prior to the recent generation of stabilized imaging platforms, there were attempts to use the plane or helicopter models for close-range photogrammetric surveys of stream restoration [11,12]. The recent development of UAVs, providing reliable and user-friendly imaging platforms for geosciences, opens up new possibilities for the detection of stream properties and monitoring at a high level of accuracy [13,14]. Customizable flight routes at low-level altitudes in combination with new algorithms for photogrammetric processing provide 2D and 3D spatial data products of very high spatial resolution, suitable for qualitative and quantitative analysis of natural and artificial structures of streams and floodplains. A number of studies proved the potential for applications of UAVs in the monitoring of the principal riverscape elements, which is important for the monitoring and assessment of the stream restoration projects. In particular, it applies to the monitoring of fluvial dynamics and the channel changes after flooding [13,15,16]. The UAV-based high-resolution data were successfully applied for the assessment of the fish stream habitat conditions [17] as well as the complex habitat monitoring [18]. High-resolution UAV data were used for monitoring of changes in floodplain vegetation [19].

UAV imaging as the resource for assessing stream restorations in the urban or suburban landscape is, however, still used sparsely. The unmanned imaging platforms, however, have the potential to be an optimum resource for objective stream restoration monitoring, balancing the needs for high spatial resolution, a combination of 2D and 3D information, complex coverage of the restoration site, and the ability for recurrent monitoring. The photogrammetric products of the UAV imaging campaigns are delivering the seamless orthoimagery and 3D models with a spatial resolution of 2–5 cm per pixel, depending on the imaging altitude and sensor type [20]. In most cases, the typical size of a restoration of a small stream in cities and suburban zones reaches 1–2 km of the stream length, which is an extent coverable by a UAV platform. Last, but not least, the UAV platforms are cost effective and allow us to design the recurrent multitemporal monitoring campaigns as well as the ad-hoc surveys.

The aim of this study was to identify the aspects of stream restoration, where the UAV imaging can bring qualitatively new information, applicable for the monitoring and evaluation of stream restorations in an urban landscape and test the appropriate photogrammetric and geoinformatic methods. In particular, the assessment was focused on the verification of the compliance of the stream restoration with the plan, analysis of the riparian habitat changes, detection of eutrophication, identification of changes of stream channel, and testing of the ability of the restored stream to cope with the flood events. The analysis is based on three years of recurrent UAV monitoring of the Hostavicky brook in Prague, Czech Republic, where a complex restoration of the stream and the riparian zone was realized in 2015.

2. Materials and Methods

2.1. Post-Project Monitoring of Stream Restoration

One specific problem of stream restorations, including the projects in the urban landscape, is the frequent lack of systematic post-project monitoring and evaluation of further evolution of the restored system [21]. Deficiency in such information makes it difficult to assess the effectiveness of restoration, to identify its positive aspects, as well as the structural problems or failures [22]. The reasons for the monitoring deficiency are manifold; ranging from the lack of suitable data sources to methodological deficiencies in project planning and management, lack of a complex approach aiming at the sustainability of the restoration, and its efficiency in a long-term perspective. This can also result from irresponsible investment strategies, benefiting from one-off funding opportunities aimed at physical restoration, but without planning of the post-project activities, including monitoring [23].

The stream restoration project always represents a complex study balancing various needs, ranging from the improvements of the hydromorphological status of a stream, the keeping of the given hydraulic properties of the structures, securing the flood protection, as well as to secure the future stability of the structures or improvements of environmental and socioeconomic status. The accordance of the realized stream restoration works to the approved study plan should thus be

regarded as a primary sign, indicating the potential for the functionality and sustainability of the restoration works in the long-term perspective. Failures in respecting the restoration plan may result in a range of substantial issues including the inadequate level of flood protection, instability of the stream channel with elevated bank or bed erosion, limited sustainability of the restoration, or unused potential for improvements of ecological and hydromorphological status.

The success of stream restoration projects largely depends on the multiple constraints and limitations given by the specifics of the given conditions, which is of special importance in urban and suburban environments. Urban streams have complex hydrology, however they feature simplified geomorphology and reduced ecological function [22]. The intense alterations of stream morphology result in flashier hydrograph, intense pollution, and reduced biotic richness [23]. Nevertheless, the potential for stream restoration in urban zones is limited. The land is usually extremely expensive and thus intensely exploited, so there is very limited space left for restoration projects. These are, especially in the inner cities, typically focused on the stream channel and its close vicinity, often excluding even the riparian zone [24]. The sub-urban zones offer more opportunities for restoration and inclusion of the wider area of the floodplain. Despite the higher restoration potential of such zones, the projects are often limited to the isolated stream segments, corresponding rather to the urban development plans than the water management [25]. The restoration is, thus, often aiming at improvements of the aesthetic aspects of urban space rather than providing a complex restoration of the hydrological and ecological functions of the hydrological system. The variety of restoration practices is another aspect making the assessment of stream restoration and selection of appropriate criteria difficult [24,26].

General principles allowing us to distinguish the restoration success have been proposed in Reference [27] as follows: (i) The design of an ecological river restoration project should be based on a specified guiding image of a more dynamic, healthy river that could exist at the site; (ii) the river's ecological condition must be measurably improved; (iii) the river system must be more self-sustaining and resilient to external perturbations so that only minimal follow-up maintenance is needed; (iv) during the construction phase, no lasting harm should be inflicted on the ecosystem; and (v) both pre- and post-assessment must be completed and data made publicly available.

Although many authors concur on the need for a system and criteria for assessment of ecologically successful river restoration, no common standards were defined or accepted [25,27]. A common agreement is in the need of a framework, allowing assessment of the success and evolution of the key aspects of stream restoration [28] based on objectively detectable parameters, e.g., water quality, channel morphology, stability after high flow events, progress in establishing native plant communities, and measuring fish and wildlife presence [29]. An example of such an approach is the framework proposed in Reference [21]. The authors proposed the following evaluation criteria for the five general objectives:

1. Channel capacity and stability (e.g., channel cross sections, flood stage surveys, width-to-depth ratio, rates of bank or bed erosion, longitudinal profile),
2. Improvement of aquatic habitat (e.g., water depth, velocities, cover, shading, pool/riffle composition, bed material composition, invertebrates, macrophytes),
3. Improvement of riparian habitat (e.g., percent vegetation cover, species densities, size distribution, age class distribution, plantings survival),
4. Improvement of water quality (e.g., temperature, pH, dissolved oxygen, conductivity, nutrients, turbidity, suspended matter, trash loading),
5. Recreation and community involvement (e.g., landscape control point surveys, recreational use surveys, participation in management).

This framework was used in this study as a basis for identification of criteria, where the UAV technologies can supply information on stream restoration. Selection of evaluation criteria focused on the aspects of monitoring, where the high-resolution imagery can bring reliable and qualitatively new information, applicable in the evaluation. From the above-stated list of criteria, it applies to the objectives 1 and 3, i.e., the changes in the physical and qualitative state of the channel and riparian zone. To these objectives, there was added a criterion of the compliance of the geometric properties

of the realized stream restoration to the plan as an important sign, indicating potential discrepancies in hydrological and ecological functions of the new system from the calculated plan. Hence, the applicability of the UAV monitoring was tested on the following aspects of the stream restoration:

a. Compliance of the stream restoration with the plan,
b. Channel stability and evolution,
c. Flood mitigation effects,
d. Changes in riparian habitats.

2.2. Study Area

The study area of Hostavický brook in Prague is a 1 km long segment of the stream in an urbanized area that underwent a complex restoration in 2015 (Figure 1). The assessed stream is located in the north-eastern boundary of the Prague metropolitan area, in a zone between the old housing and new development area. The stream was channelized in the 1980s during construction of the new road and highway infrastructure in the area. For three decades, the study area was an abandoned zone of the sub-urban "new wilderness" [30,31], featuring a spontaneous succession of vegetation over the former agricultural land without management. In consequence of development of new residential complexes, the City of Prague in 2015 realized a project of a complex revitalization of the area, aimed not only to the restoration of the meandering system of the stream, but also to build the recreational infrastructure for the public, including the cycle route, playgrounds, and park [32]. The key elements of the restoration of Hostavický brook, the stream corridor, and ponds were finished in November 2015. The whole complex of restoration works, including the grassing of the riparian zone and planting of trees stabilizing the newly built channel, was opened in spring 2016.

Figure 1. Study area of Hostavicky brook, Prague. (**a**) Map of the study area, (**b**) stream channel prior to restoration, (**c**) stream restoration works on the channel, (**d**) aerial view of the stream one year after restoration. Photo by J. Langhammer.

The study site is subject to frequent flooding of low magnitude, resulting from the spring and summer rainstorms. Since the restoration in fall 2015, several rainstorms have been recorded resulting in local flooding, e.g., in June 2016, August 2016, June 2017, and June 2018. The most intense flood recorded in the area for the last decade was the event on June 29, 2017. The city of Prague was then hit by a heavy rainstorm with the precipitation totals of 80–110 mm per 24 h, while most of the precipitation totals were recorded in 12 h. The study site is not equipped with a direct meteorological or hydrological station, however, the monitoring in the neighboring stations in Prague indicated that the magnitude of the event corresponded to a recurrence period of 20–100-year precipitation. The consequent flood in the area resulted in extensive spills, local landslides, and damage to residential zones [33]. This flood was thus used for testing the capacity of the newly designed stream system and its ability to cope with a flood event of medium magnitude.

2.3. UAV Monitoring Setup

The UAV monitoring in the study area was undertaken for three years after the restoration works. In total, 29 imaging campaigns were realized over two years, from September 2015 until April 2018. Two initial campaigns were done by the DJI Phantom 2 Vision plus platform (DJI, Shenzen, China), and the 27 following campaigns then performed by the DJI Inspire 1 Pro system.

Figure 2. UAV platform DJI Inspire 1 Pro, used for monitoring campaigns. Photo by J. Langhammer.

The Inspire 1 Pro platform (Figure 2), used for the imaging since November 2015, is driven by four propellers, enabling a flight of a length of 15–22 min, according to the payload. The maximum distance of the control system is 2 km, the physical maximum altitude of 1 km [34] is, in practice, limited by the legislation regulations, limiting drone traffic at a level under 300 m above ground. The control system of the drone also allows, besides the manual control, the flying of pre-programmed routes, which was used for the recurrent imaging campaigns. The platform was equipped with the DJI Zenmuse X5 camera (cDJI, Shenzen, China) with interchangeable lenses, equipped for this study with the 12 mm Zuiko prime lens (Olympus, Tokyo, Japan) with 84° field of view (FOV), 24 mm equivalent in 35 mm system, and with a Zenmuse X3 camera (DJI, Shenzen, China), featuring a fixed lens with focal length 3.6 mm (94° FOV, 20 mm equivalent in 35 mm system). The X5 camera has a 17.3 × 13.0 mm CMOS sensor of micro 4/3 standard, featuring a resolution of 4608 × 3456 pixels (16 Mpix), capturing in Red, Green and Blue (RGB) spectral bands. The X3 camera features a Sony EXMOR 1/2.3″ CMOS chip (Sony, Tokyo, Japan) with a resolution of 4000 × 3000 pixels [34]. The DJI

Phantom Vision plus, used for the first two campaigns, is a multirotor platform, equipped with a 14 Mpx panchromatic camera with a resolution of 4384 × 3288 pixels and a fixed lens with 5 mm of focal length and 110° FOV, equivalent to 18 mm for 35 mm system [35].

The imaging campaigns were scheduled in a bi-monthly interval with exceptions in winter when the stream was under snow cover. During the period of extensive construction works on the stream restoration in 2015 and during the flash floods, the regular campaigns were completed by additional imaging (Table S1).

The imagery was taken from an altitude of 50–70 m above ground, resulting typically in 290–320 images per campaign and sensor. The design of the flight route was set to cover all the key components, important for the hydromorphological status of the stream and the riparian zone (Figure 3a). The pre-programmed flight plan for imaging was designed to cover the area with a 70% front and side overlap (Figure 3b). One imaging campaign consisted of 2–3 flights of approx. 15 min each, according to the weather conditions affecting the flight time. As a result, the complex segment of a stream in a length of 1 km is covered by a multitemporal set of seamless orthoimagery with the resolution of 1.3–1.7 cm per pixel according to the applied sensor and flight altitude (Table S1).

For georeferencing, 26 ground control points (GCPs) were used. The control points were defined at the stable structures of the urban environment, which are apparent in the imagery and have geodetically surveyed position available from the digital city plans, such as sewer lids, edges of buildings, or concrete structures (Figure 3c). From the total of 26 GCPs, 15 were used as control points for georeferencing and 9 as checkpoints to validate the accuracy of photogrammetric processing. Mean differences in x and y coordinates at the checkpoints typically reached 1.5–3.5 cm, while the maximum differences, observed at the outer parts of the scene, did not exceed 10 cm.
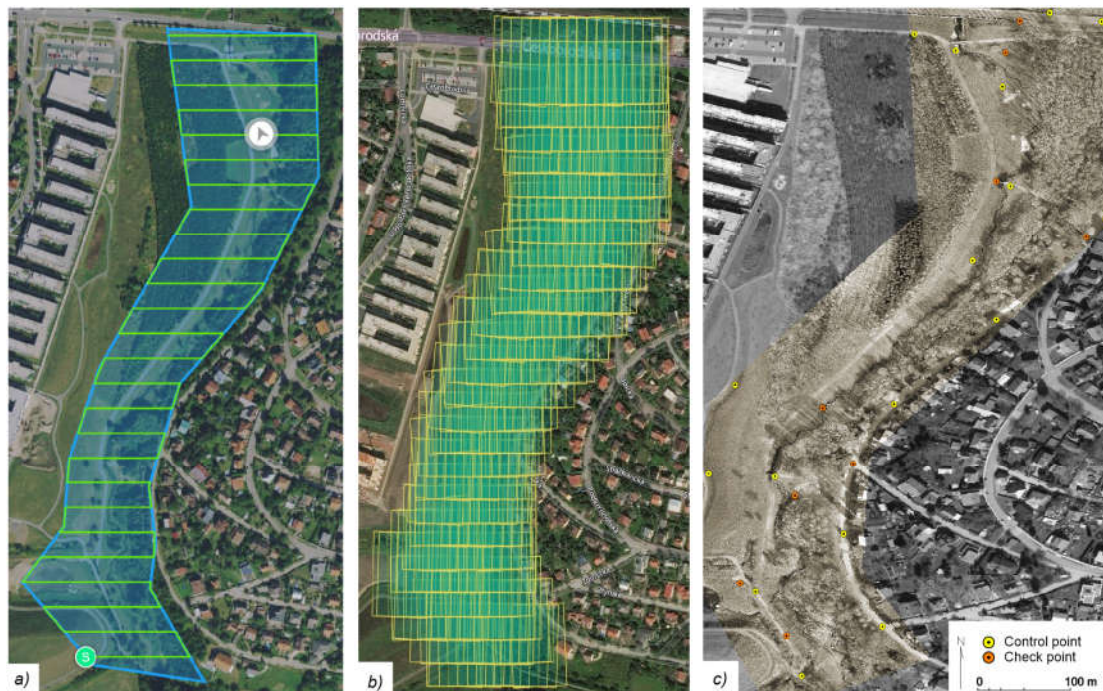

Figure 3. UAV imaging campaign. (**a**) Flight route planning. Screenshot from GroundStation Pro software. The green mark represents the start-point of imaging; at the upper end of the stream segment, the green line represents the flight track and the grey arrow mark indicates the take-off position of the drone. (**b**) Location, coverage, and overlaps of the 292 images, resulting from the flight track, used for the photogrammetric analysis. (**c**) Distribution of control and check points in the study area.

2.4. Photogrammetric Processing

The nadir UAV imagery was used for the photogrammetric reconstruction using the structure from motion (SfM) algorithm, enabling automatic determination of the elements of internal and external camera orientation from the aerial imagery [36]. This approach enables us to perform a reconstruction of the 3D topography from the imagery taken from different viewpoints and even combining the imagery taken in nadir and oblique angles [14,36]. The automation of image alignment, ability to cope with unstructured imagery, and availability of complex software tools have eliminated the key constraints of conventional photogrammetric approaches and stimulated the recent upswing of UAV applications in geosciences [37].

The photogrammetric workflow based on the SfM approach consists of several steps—(i) the acquisition of the imagery with adequate front and side overlaps, (ii) detection of corresponding pairs of points for aero triangulation and image alignment, forming a sparse cloud, (iii) generation of dense point cloud, from which are derived two key deliverables: (iv) The digital surface model (DSM) and (v) the orthoimage [38].

Two photogrammetric tools with different workflows and requirements for computing equipment and photogrammetric skills of operators necessary for processing were used. The Agisoft Photoscan Pro 1.4.1 desktop software [39] was used as a primary tool for complex photogrammetric processing of the imagery. This photogrammetric suite allows the control of the whole processing workflow with detailed settings of all parameters. A PC-based workstation, equipped with Intel Core i7 processor (Intel, Santa Clara, CA, USA), 64GB DDR4 RAM, and two Nvidia GTX 970 GPU (Nvidia, Santa Clara, CA, USA) acceleration units was used for data processing. The processing of one imaging campaign with the highest quality setting required typically 9–15 h of processing time. As the supporting processing tool, the cloud-based DroneDeploy tool [40] was used. This cloud-based service allows an easy and rapid photogrammetric of UAV imagery without demanding computing equipment. In this study, the DroneDeploy tool was used for immediate checking of the data quality and consistency of the imagery before the full photogrammetric processing of the datasets. Such preprocessing required typically 1–2 h of cloud computing for one imaging campaign.

The photogrammetric processing of imagery from the recurrent imaging campaigns resulted in a multitemporal set of 29 orthoimages, spanning from September 2015 to September 2018 (Table S1). The orthoimages, featuring native resolution from 1.2 to 1.55 cm per pixel according to the flight parameters were sampled to a uniform resolution of 2 cm per pixel, adequate for identification of the stream and floodplain features (Figure 4). From the orthoimagery, there were quantitative and qualitative indices derived, applicable for the stream restoration assessment.
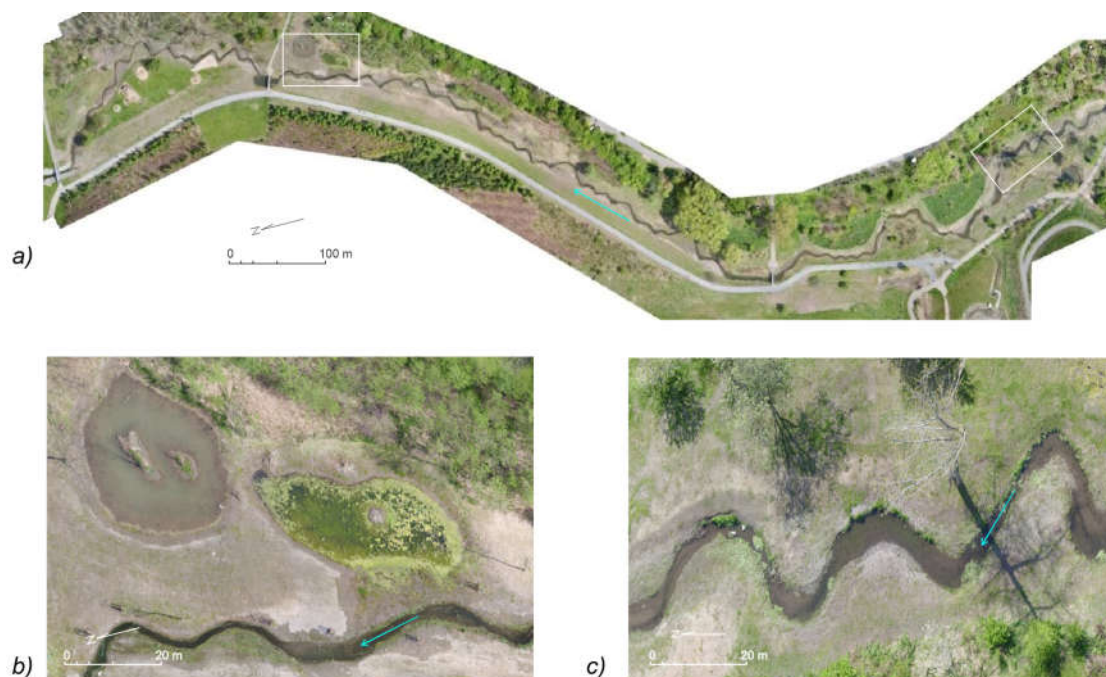
Figure 4. Orthoimagery of Hostavicky brook from June 2016. (**a**) Overview of the study site, (**b**) detailed view of the newly built ponds, (**c**) detailed view of the newly designed meanders of the stream.

2.5. Analysis and Processing of the UAV Orthoimagery

The UAV-based imagery was used for the analysis of different aspects of the status and changes in the riverscape, using different techniques for extraction of the spatial, quantitative, or qualitative information from the imagery. In particular, it applied to the extraction of linear features (reflecting the changes of the stream channel), the areal features (expressing the spatial extent of vegetation or water spills), as well as the analysis of qualitative changes in the riparian zone and eutrophication processes.

2.5.1. Delineation of Geometric Properties of the Channel

To extract the shape of the stream line from the high-resolution imagery, different approaches are used in the literature. The common methods use conventional manual digitizing of the stream line from the orthoimages [41], automated detection, employing the techniques based on separation from the multispectral image [42], or techniques based on the topographic supported approaches [43]. Another option for the automated delineation of the stream channel represent the graphical tracing algorithms used i.e., in historical cartography [44]. However, for hydrological application, such approaches are typically applied on medium-sized and large rivers, where the stream can be distinctly separated from the background. In the studied environment of a small urban stream, the narrow channel is, in several parts, obscured by the riparian vegetation, which makes the fully automatic stream delineation uneasy, so a semi-automated approach was used.

The extraction of the stream line from the orthoimagery was used for the assessment of the compliance of stream restoration with the plan and for the detection of the channel evolution after the restoration. The Vextractor tracing software [45] was first used to derive the basic shape of the stream line (Figure 5). The automated vectorization allows deriving either the stream centerline or outline and both options were used for different tasks. The stream centerline was derived for analysis of the compliance of the newly restored stream with the initial plan. The outline was then used for detection of the river line for tracking the changes of the channel since the restoration.

Figure 5. Automated delineation of the stream centerline using Vextractor tool with a detail of the interruption of the line at the location of in-stream obstacle.

The use of UAV imagery as a basis for vectorization was met with several constraints related to the very high resolution of the data. The delineated stream features were interrupted at locations of in-stream obstacles (Figure 5), glares on the water surface, or in spots covered by the vegetation, so the extracted stream line requires further manual corrections. The stream line delineation in this study thus combined the automatic delineation with consequent manual corrections. For vectorization, there were selected orthoimages from the spring season, featuring minimum vegetation coverage and low-water-level conditions, enabling good recognition of the stream features.

Upon the delineated vector shapefiles, there were basic hydrographic indices of geometric properties of the stream derived and calculated. In particular, there was counted a number of meanders, derived values of mean meander amplitude and wavelength [46], and calculated index of stream sinuosity, expressed as the ratio of the channel and valley length. Stream sinuosity index was derived for the main stream segment using the RiverMetrics tool in QGIS software [47]. The calculation is done using a floating window with parameters set to a distance of 200 m and sampling interval of 50 m.

All indices were calculated for three states of the stream system—prior restoration, restoration plan, and realized restoration. The status prior stream restoration and of the restoration plan were acquired as vector geodatabase [32] and the status of realized restoration was derived by the vectorization of the UAV orthoimagery. As the reference post-restoration status, the imaging campaign from April 2017 was selected, reflecting the stabilized channel after cca 1.5 years since the restoration completion. The spring imagery was selected as suitable for capturing the stream properties in the off-vegetation season, enabling the display of the possible maximum of the stream and floodplain features (Figure 4).

2.5.2. Detection of the Extent of Flood Spill

The detection of a spatial extent of the flood spill from the UAV high-resolution imagery was done by supervised classification, being a basic method in conventional remote sensing [48]. Compared to the conventional remote sensing techniques, the use of the high-resolution RGB imagery for supervised classification meets with several constraints. The classification of natural phenomena is best performed on a multispectral or hyperspectral imagery, where the objects can be described by multiple bands, mixing the visible (VIS), near-infrared (NIR), or infrared (IR) part of the spectrum [49], which allows distinction and qualitative assessment of land cover properties [50].

However, the use of multispectral UAV sensors, although promising, [51,52] in practice still remains limited to experimental studies, mostly due to the high costs and demands for skilled operation and data processing. Most of the conventional UAV platforms used for surveying is, hence, equipped with the RGB cameras. This study thus aimed to test the ability of the RGB sensors to provide the information suitable for qualitative analysis and data-driven identification of the features of the riverscape and applicable in restoration management.

Use of VIS bands only for classification is related to known difficulties, as such imagery containing the objects of different functional categories but a similar color response in RGB channels [10]. To enable the appropriate distinction of the objects, the classified features should have unambiguous spectral response to avoid mixing of the classification categories. In this study, the separability of the features was secured by limiting of the classification area to the mask of the zone of interest, which allowed the exclusion of the features with a similar color response, bringing noise to the classification. Under the mask, the extent of the given features was detected using the supervised classification.

The classification was done in the SAGA GIS software [53] using the supervised classification module. The training samples of the water level, sized at 60–380 pixels, were selected in five different parts of the study area to cover the potential variability of the reflectance values of the water level in

different zones of the study site. Based on these training areas, the supervised classification of only one class (the water level) was performed using the parallelepiped method [54]. This approach was applied both for the case of detection of water spill and vegetation cover.

The detection of water spill was tested on the case of a flood in June 2017. The source imaging of the restored stream segment was taken during the crest of the flood, June 29, 2017, at 17:00 CET.

2.5.3. Detection of Changes in Riparian Habitats

Monitoring of riparian habitat changes related to the restoration projects covers a variety of measures, realized in the framework of complex restorations, aimed at restoring the natural biological habitat, increasing biodiversity, or to improve the aesthetic aspects or recreational functions of the stream in the urban environment [27]. The vegetation changes typically include grassing of the riparian zone, artificial tree plantation, the spontaneous succession of vegetation, but also the overgrowth of vegetation in the oxbow lakes or ponds [55].

In this study site, the progress of overgrowing and eutrophication in the newly created ponds was tracked based on the UAV imagery. The newly built ponds in the floodplain of Hostavicky brook became subject to spontaneous overgrowing and eutrophication processes since the restoration completion (Figure 6).

Figure 6. The newly created ponds in riparian zone, left without hydrological connection, featuring eutrophication. Orthoimage from April 30, 2016.

Analysis of the course of these processes was based on the application of the spectral indices, calculated from the RGB orthoimages. The analysis was here limited to the area under the mask, delineated according to the water extent of the new ponds.

For the analysis, there were selected spectral indices, that proved the ability to detect the vegetation status from the RGB spectral bands from the UAV imagery [56–58]. In particular, three indices were applied: Green–red vegetation index (GRVI, Equation (1)), which was successfully tested for detection of crop cover biomass from uncalibrated RGB UAV sensors [59]; visible atmospheric-resistant index (VARI, Equation (2)), that indicated promising performance in the detection of grassland [60]; and the visible-band difference vegetation index (VDVI) whose accuracy in vegetation extraction was positively rated in Reference [56]. The indices were calculated as follows:

$$\text{GRVI} = (G - R)/(G + R) \tag{1}$$

$$\text{VARI} = (G - R)/(G + R - B) \tag{2}$$

$$VDVI = (2 \times G - R - B)/(2 \times G + R + B) \qquad (3)$$

For all indices, there were calculated values for the spring and summer season following the restoration with five time slices from January until September 2016. For the analysis, the minimum, maximum, mean, and quartile values were calculated for the area under the mask of the extent newly built ponds (Figure 6). Calculation of indices as well as the grid statistics was done using the SAGA GIS grid calculator and grid statistics tools.

3. Results

3.1. Compliance of the Stream Restoration with the Plan

Comparison of the stream pattern of the Hostavický brook after restoration with the original plan proved general fulfillment of the principal goals of the restoration project but also revealed the significant differences of the stream features compared to the restoration plan.

The general accomplishment of the basic goals of the restoration is evident from the calculation of basic geometric properties of the remodeled stream and riparian zone (Table 1). Restoration converted the previously straight stream, channelized using the concrete profiles, into a meandering stream in a flat riparian zone, featuring diverse flow velocities and providing conditions for spontaneous development of riparian vegetation. The stream sinuosity raised from 1.03 prior restoration to the resulting 1.25 and the initially straight stream recently featured 94 meander bends and 3 ponds (Table 1).

Table 1. Geometric properties of the initial, planned, and restored stream segment.

Stream Status	Stream Length (m)	Index of Sinuosity	Number of Meander Bends	Number of Ponds	Average Meander Wavelength (m)	Average Meander Amplitude (m)
Prior restoration	845	1.028	0	0	-	-
Restoration plan	1076	1.385	121	2	10.5	7.9
Post restoration	979	1.246	94	3	16.8	12.3

However, there were multiple and significant discrepancies identified between the planned and resulting status in the shape of the restored channel (Figure 7). From the geometric properties of the planned and resulting stream course, it is apparent that the resulting structure is less complex than planned (Table 1). A significantly lower number of meander bends than planned were built—4 instead of 121. The average amplitude of the then correspondingly increased from the planned 7.9 to 12.3 m. As a result, the built channel features also lower length and sinuosity than was planned.

The nature, extent, and location of the discrepancies are apparent from the GIS overlay of the planned and resulting status (Figure 7). First, the course of the whole newly built meandering belt substantially deviated from the approved plan in four stream segments, marked A, B, C, and D (Figure 7c). Second, there is apparent different size and amplitude of the newly-built meanders in the central part of the stream restoration. The scope of deviations from the plan is apparent from the different distribution of the stream sinuosity along the main stream segment (Figure 7d). Third, from the post-restoration status, there is apparent significant difference in location of the newly built ponds in the riparian zone. Some of the planned structures were not built at all, while others were constructed. Moreover, the newly built ponds have no surface hydrological connection with the stream.

The extent of changes and deviations from the plan is substantial, with the potential to affect the proposed eco-hydrological properties of the restored stream structure. Hence, there emerges a vital

need for further post-restoration monitoring of the restored stream to track the appropriate hydrological as well as ecological functions of the restoration under varying conditions.
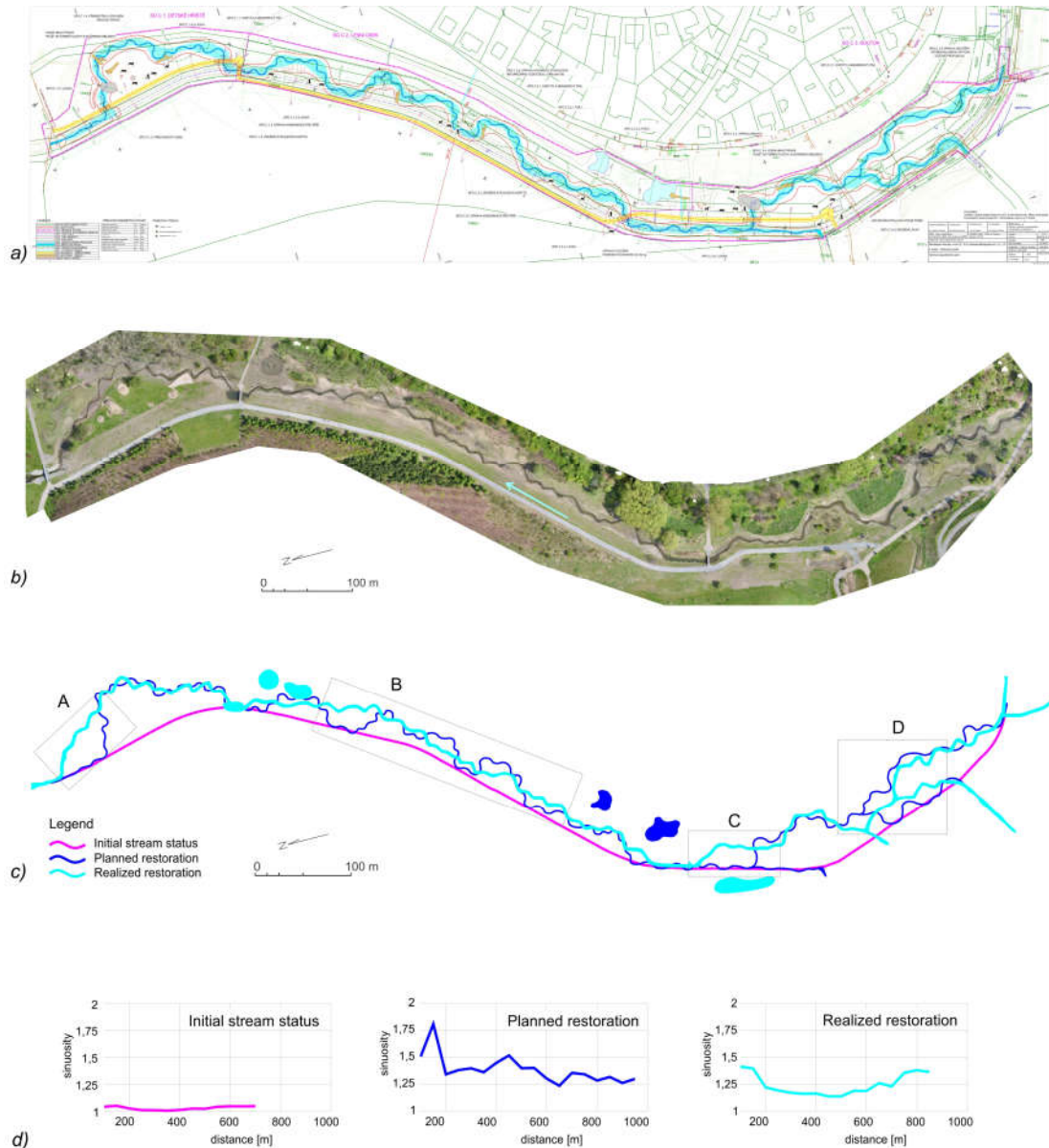

Figure 7. Fit of the resulting stream restoration to the plan. (**a**) Initial status and plan of the restoration, (**b**) newly shaped channel, six months after restoration, (**c**) identification of stream segments where the restoration has deviated from the plan, and (**d**) changes in stream length and sinuosity.

3.2. Stability of the New Channel

Over the three years since the stream restoration, the restored channel of Hostavický brook proved the overall stability. Neither the newly built meander bends nor the riparian zone experienced substantial changes, even after the peak flows in June 2016 and 2017.

The comparison of changes between spring 2016 and 2018 proved general stability of the channel with no traces of intense fluvial activity. There were two spots identified with traces of successive bank erosion and consecutive meander cutting (Figure 8). The overbank flow during the flood events initiated formation of the straight cut-off segments that are further evolving and naturally shortening the stream line. The stream development was facilitated by the absence of bank reinforcement by

vegetation in the first year since restoration, when the newly created stream in the floodplain was formed by bare land.
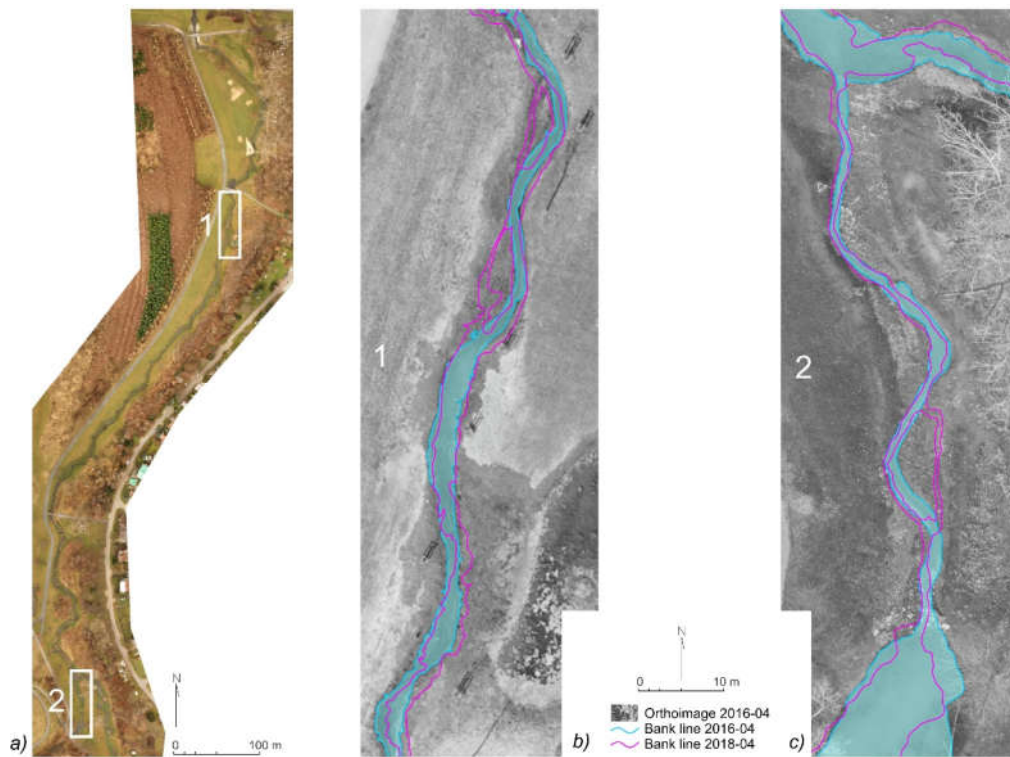

Figure 8. Evolution of the meandering system after restoration between April 2016 and April 2018. (**a**) Location of two segments where changes were detected. (**b**) Cutting of a meander in the stream segment 1, (**c**) channel changes in the segment 2.

The overall stability of the new channel was supported by coherent grassing of the restored riparian zone. The stream channel redesign was a part of the complex restoration of the floodplain, formerly covered by ruderal vegetation. The space for the newly formed meandering system was clear-cut from the succession vegetation and the riparian zone was completely remodeled and grassed. Since the completion of the construction works, grassing of the meandering belt and plantation of trees was started (Figure 9). The successful grassing of the riparian zone is a positive sign for the sustainability of the restoration as it helps to support the stability of the channel system and mitigate the potential bank erosion.

Figure 9. Vegetation succession in the riparian zone of the Hostavicky brook. (**a**) Bare surface of the newly built meandering belt in September 2015, (**b**) coherent grass cover in the same stream segment in April 2018. Photo by J. Langhammer.

3.3. Restoration Effect on Flood Mitigation

The potential of the newly restored channel to mitigate the flood events was tested by the flood in June 29, 2017, when a UAV imaging during the crest of the flood was taken to capture the extent of water spill in the newly shaped floodplain. The resulting orthoimage was used as a basis for the supervised classification of the water extent during the flood event (Figure 10).
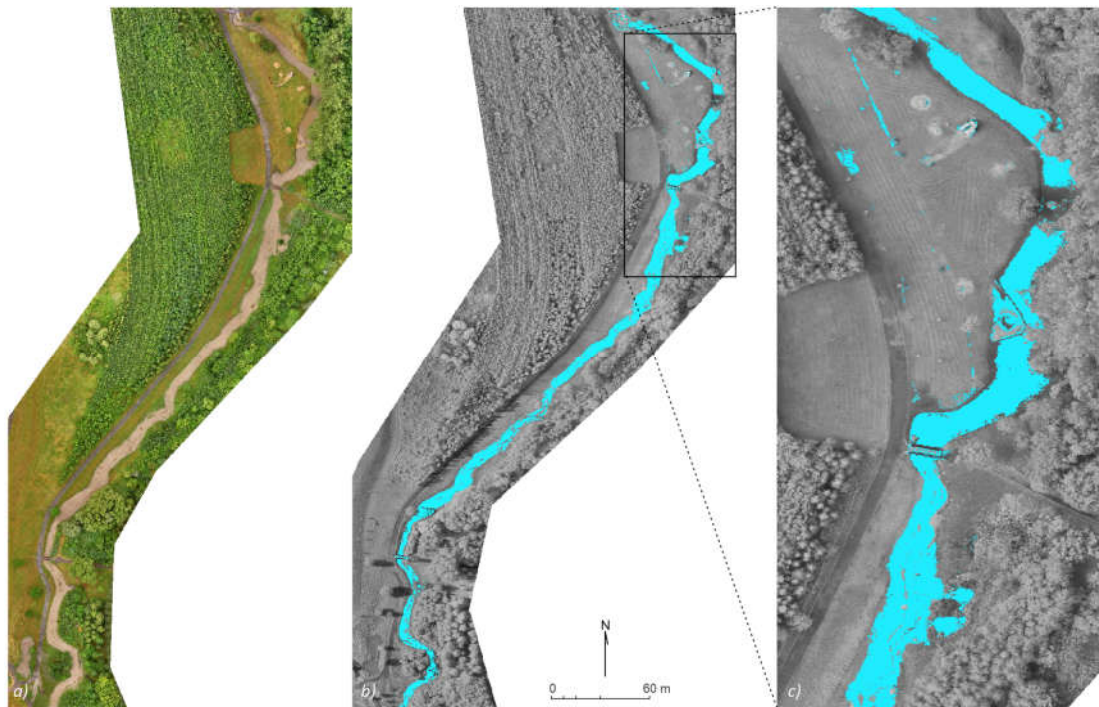

Figure 10. Detection of the extent of the flood spill during the crest of flood in June 29, 2017. (**a**) Orthoimage of the Hostavicky brook during the flood crest, (**b**) Classification of the water extent during the flood crest in the study area, (**c**) Detailed view to the classification results.

From the classification results (Figure 10) it is apparent that the flood fully used the space of the meandering belt. From the detailed view to the flood spill extent (Figure 10b,c), there is also apparent overbank flow, temporarily connecting the stream with the newly built ponds. The water level exceeded the limits of the relatively shallow stream channel but was kept inside the inner space of the riparian zone and in the floodplain, there were not detected any spills outside the meandering belt. This indicates appropriate hydraulic properties of the stream, which is important in spite of the extent of deviations in stream restoration from the original design.

The extent of flooding, detected by classification, was further checked in the field by observation of the typical traces of the flood in the floodplain, as is the compressed and mudded grassland in the zones of the spill. The isolated spots of water, apparent in the classification outside the stream (Figure 10c) belong to the wet spots and puddles, emerging in the flat land after the rainstorm.

3.4. Changes in the Riparian Habitats

Besides the planned grassing and tree plantation, the stream restoration also initiated a spontaneous succession of vegetation in the riparian zone. During the first year since restoration, significant eutrophication and a vegetation overgrowth were detected in the newly created ponds. The rapid succession was apparent in the ponds built in the lower part of the restored segment without a direct hydrological connection to the stream (Figure 11). The lack of surface drainage of the ponds resulted in extensive eutrophication and overgrowth of reed (*Phragmites australis*).
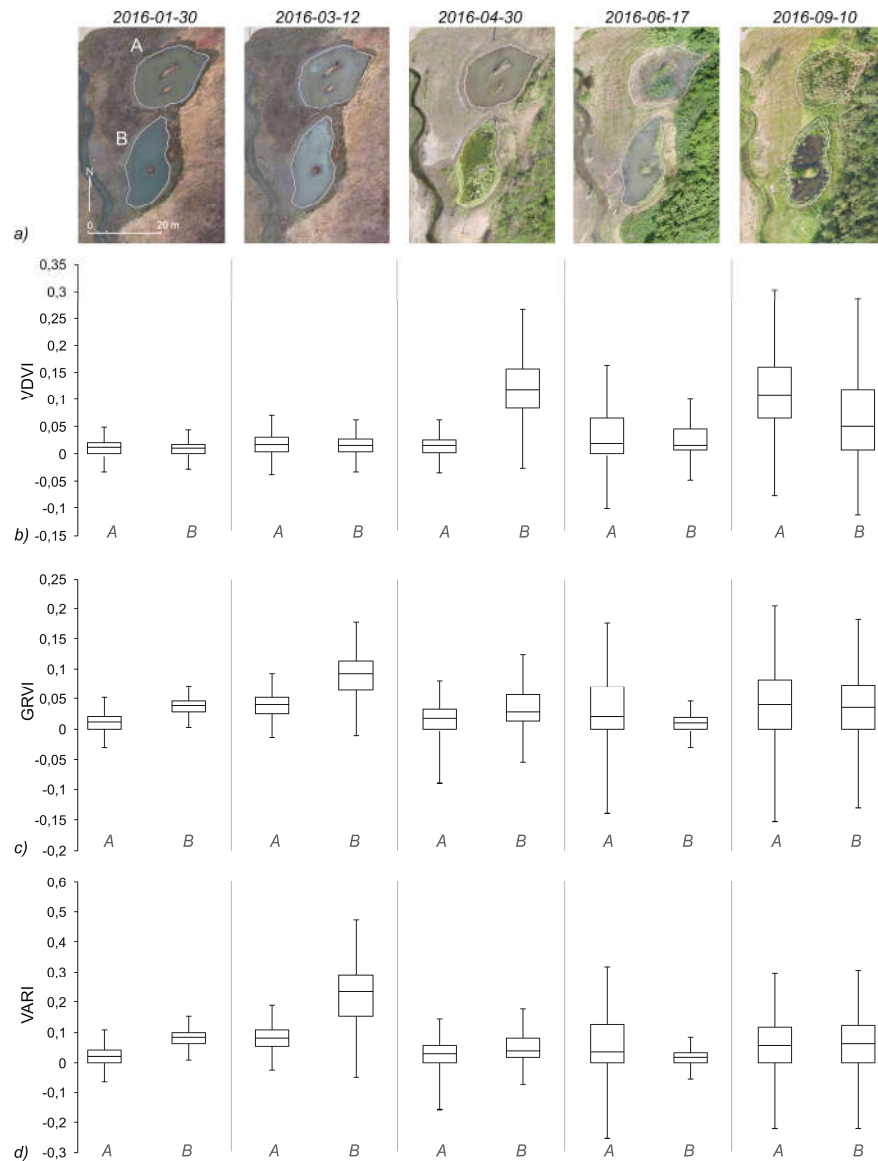
Figure 11. Vegetation overgrowth and intense eutrophication in the newly created ponds over the first vegetation season since the restoration. (**a**) RGB imagery, (**b**) visible-band difference vegetation index (VDVI), (**c**) green–red vegetation index (GRVI), (**d**) visible atmospheric-resistant index (VARI).

The progress of overgrowing and eutrophication is well apparent from the UAV imagery (Figure 11). In the spring season of 2016, pond B was first affected by heavy eutrophication, apparent in the imaging from late April. After the spring storm in the beginning of June 2016, both ponds were flooded and drained, which is reflected in the imagery from mid-June 2016. Over the summer season, the eutrophication in pond B restarted, at the same time pond A became overgrown by reed. The same pattern of the overgrowing and eutrophication in both ponds then appeared in both following years (Figure 12).

From the three indices used for detection of the eutrophication and overgrowth—RVI, VARI, and VDVI—mentioned in the literature as suitable for the detection of vegetation fraction from the RGB imagery [56–58], only the VDVI index correctly ascribed the dynamics of the processes in riparian zone (Figure 11). The distribution of the VDVI index values, calculated under the mask of newly created ponds (Supplementary data, Table S2), correctly reflected the variability of changes in both ponds and distinctly reacted to the intensity of eutrophication processes. On the contrary, both

VARI and GRVI indices, calculated from the same imagery, were unable to correctly track the water eutrophication, nor the pond overgrowing.
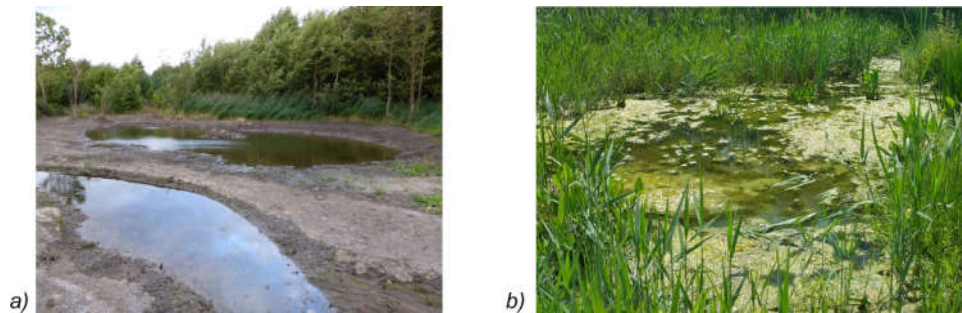

Figure 12. Eutrophication and vegetation overgrowing in the newly built ponds. (**a**) Pond B with apparent lack of hydrological connection to the stream during construction works in September 2015, (**b**) vegetation overgrowth and eutrophication in the pond B in April 2018. Photo by J. Langhammer.

4. Discussion

Three years of UAV monitoring of a post-restoration evolution of an urban stream revealed positive as well as negative aspects of the studied urban stream restoration and also enabled the testing of various aspects of the applicability of the UAV surveying for post-restoration monitoring.

First, the post-restoration monitoring of the Hostavicky brook proved that the basic hydrological and hydromorphological aspects of the restoration were fulfilled. The stream was reshaped from a straight channel with a uniform profile into a meandering stream with a diversity of flow and potential for spontaneous development of habitats. However, the UAV survey revealed that the stream planform of the realized restoration significantly diverged from the plan. The whole meandering belt in several segments deviates from the planned direction (Figure 7) and the resulting stream has a substantially lower number of meander bends and features lower sinuosity than was planned. The designed wavelength and amplitude of new meanders were not respected in most of the parts of the restored segment. Instead of two artificial ponds, there were three built, but in different locations and with no hydrological connectivity to the stream.

Despite such extensive changes of the stream properties, the spill of the flood in June 2017, belonging to the major known events in the area, indicated the proper hydrological function of the newly shaped stream. The channel was able to keep the flood spill inside the riparian zone and after the flood, the channel remained stable without significant traces of erosion or accumulations except for two minor spots of spontaneous channel development. Hence, from the hydrological point of view, despite the proven discrepancies from the plan, the stream restoration fulfills the basic needs of flood protection in the urban area. The improper design of the artificial ponds with no hydrological connection to the stream, however, led to intense development of eutrophication and reed overgrowing of the ponds since the restoration completion. This phenomenon, tracked since the restoration completion, repeats in subsequent spring and summer seasons.

The revealed problems with not respecting the stream restoration plans are frequently mentioned in the restoration assessment studies [21,25,61]. However, the conventional surveying methods and data sources, e.g., the field survey protocols or aerial imaging [62,63], provide limited possibilities for detection of such changes due to the low level of detail and timeliness of the surveys. The very high level of spatial resolution, reliability, and the ability for multitemporal surveys suggests the UAV imaging to be a suitable information source for rapid mapping and identification of discrepancies in realization from the design. Unlike the rapidly growing number of UAVs applications in a natural environment, their use for assessment of stream restoration in the urban landscape is, however, sparse.

Compared to the natural environment, the streams in urban areas feature specific properties. The streams often feature narrow channels, riparian zone constrained by the city plan and infrastructure, and experience heavy modifications due to the intense development in the urban area

[24,64]. Hence, monitoring and evaluation of the stream restoration projects and evaluation of their progress here require high spatial resolution and precision, enabling monitoring of the physical properties of small streams with high operability, able to track the changes in the urban environment as well as the effects of significant events, typically floods. For such applications, the rapidly evolving UAV technologies open up a highly perspective means of surveying. The unmanned platforms feature high versatility, especially due to the ability to carry different sensors according to the given task [18–20,65]. The 2D and 3D spatial data acquired from the UAV photogrammetry allows the derivation of information about stream channels and floodplains with spatial resolution superior to the conventional data sources [66]. The orthoimagery, typically featuring a resolution of 2–3 cm per pixel, allows the detection of even the fine details of fluvial features and allows the tracking of the changes of stream properties and fluvial forms [20].

The reconstructions based on UAV imagery remain, however, limited by the optical nature of sensing. The optical sensor cannot record the points that are not directly visible, e.g., the areas obscured by the vegetation or in submerged zones [17,67]. In part, such effect can be minimized by the appropriate scheduling of the imaging campaigns to the periods of low water levels and off the vegetation season (Figure 13).
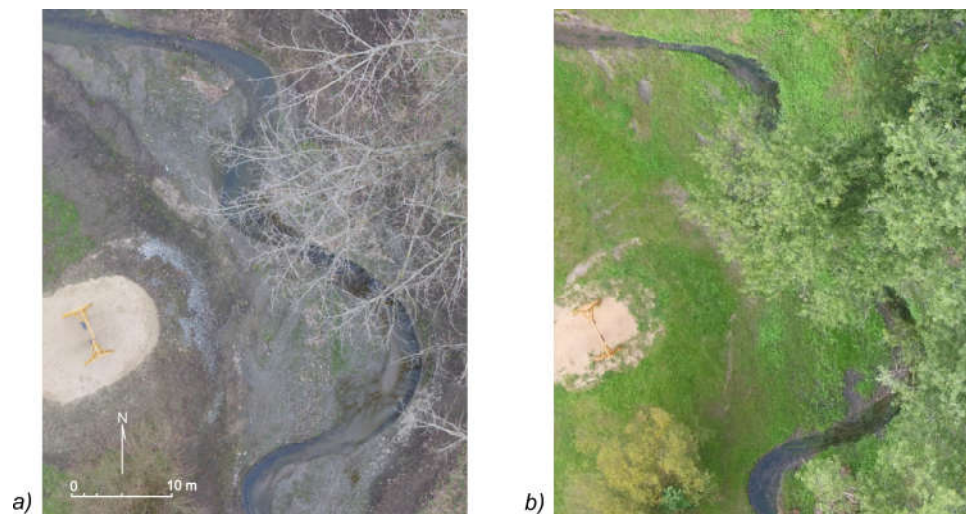

Figure 13. Stream, covered by riparian vegetation. (**a**) View of the stream through bare tree branches in March 2016, (**b**) a view partially obscured by the leaves in August 2016.

Very high resolution of the UAV imagery is, for some analytic methods like the automated tracing, bringing new types of issues, uncommon in conventional spatial data. In visible bands, the color variability of the water surface, glares, or the traces of turbulent flow makes the spectral response of the water surface inconsistent. Such variability brings noise to classification and calculation of vegetation indices. For tracing algorithms, it makes it difficult to treat the stream as a consistent unit and to reliably delineate the water body and its features. The same issues apply also to the classification and detection of the vegetation features, where the shadows are significant source of noise for detection and classification of features. In general, the inhomogeneity of the spectral response of the surface is rising with the spatial resolution of the imagery. A low level of generalization results in a similar spectral response of different surface categories [10]. This problem can be diminished by the use of near-infrared or multispectral sensors [68,69]. Although the commercial UAVs are typically equipped with RGB cameras, the advanced platforms, used mostly in research or agriculture use the multispectral or thermal sensors, enabling the analysis of qualitative landscape features [51,70]. The multispectral sensors enable distinction of the water level from the riparian zone as well as reliable classification of vegetation cover in the floodplain using methods common in conventional remote sensing [3]. However, for the routine mapping operations, the use of multispectral UAV sensors still remains limited mainly due to the high costs of the sensors, the

need for supporting calibration equipment, and, especially, the demands for skilled specialists for multispectral image processing and analysis.

This study proved that the UAV imagery in visible bands can also be used alonsgside the rapid mapping for a qualitative analysis of the riparian habitats. The spectral limitations of RGB sensors may be partially bypassed by limiting the analysis to the area under the mask of the study spot, which helps to minimize the false detection of features with similar spectral response but of different functional categories. This can be demonstrated by the detection of eutrophication processes in the new ponds using the VDVI index. Here, the reliable application of the indices calculated from visible bands was enabled by the restriction of the analyzed area to the mask of water extent. Testing of three vegetation indices based on RGB imagery proved substantial differences in their reliability. Although all of the indices have proven their performance in the literature, it is apparent that the results from specific case studies [56–58] should always be taken with caution and verified in conditions of the given environment. In this study, from the three tested indices, only VDVI index was able to correctly reflect the dynamics of the eutrophication and overgrowth when applied to the selected area under the mask of the ponds and is thus promising for applications in tracking the riparian processes. On the contrary, in the conditions of riparian vegetation in mid-latitude small urban stream, both GRVI and VARI indices were unable to correctly track the eutrophication, nor the overgrowth of the ponds.

One of the critical aspects for the success of the restoration monitoring is the appropriate frequency and scheduling of the monitoring campaigns [62,71]. In this study, the imaging was set to a bi-monthly period for three years since the restoration works. Appropriate setting of the imaging interval is essential to keep a balance between the need to capture the changes and possible burden by excessive data. The three years of monitoring proved that in the case of successful restoration, the bi-monthly interval is relevant in the initial period of restoration to verify the stability of the new channel and the start of succession processes in the floodplain. Since then, the frequency of monitoring could be set to 1–2 campaigns per year, scheduled in the off-vegetation season. Such monitoring frequency, eventually completed by ad-hoc imaging after significant events, e.g., floods or construction works, would also correspond to the standards for hydromorphological mapping [71,72]. The ad-hoc campaigns, launched after significant events with the potential to affect the stream morphology, typically floods, can help to assess the course of the events, to study the response of the restored channel and its resilience to the events of a given magnitude. For such ad-hoc rapid mapping campaigns, the operability of UAV photogrammetry is unparalleled, compared with the conventional survey techniques.

5. Conclusions

Three years of UAV monitoring of an urban stream after a complex restoration enabled the assessment of the post-restoration evolution of the channel and floodplain and to test the potential of this technology to be used for stream restoration monitoring.

UAV imagery proved to be a reliable source of detailed spatial information, applicable for the assessment of the post-restoration changes in stream and floodplain. In particular, the RGB orthoimagery was successfully used for semi-automated delineation of stream line, for supervised classification of the extent of water spill during a flood, classification of the extent of grassing, as well as for calculation of spectral indices, enabling the tracking of the eutrophication processes in newly built ponds. Performing the classifications under the mask of the given studied phenomena enabled the diminishment of the major limitation of RGB imagery—the mixed spectral response of the qualitatively different types of land cover. This approach was tested with success in the cases of classification of the extent of grassing, detection of water level during the flood, as well as for calculation of spectral indices for tracking the eutrophication. Testing of different spectral indices on RGB imagery for tracking the eutrophication processes in new ponds proved the good sensibility of the VDVI index, which was able to reliably reflect the changes in eutrophication and vegetation overgrowing of the ponds.

In the study site, UAV monitoring revealed the substantial discrepancies between the realized restoration and the plan. The realized restoration is significantly less complex, with fewer meander

bends, lower overall sinuosity, and deviations of the course of the meandering belt from the approved plan. It also proved that the new ponds were built in unplanned locations and without hydrological connection to the stream. The remodeled floodplain was the subject of intense vegetation succession, both planned and spontaneous, and heavy eutrophication in the new shallow ponds was detected.

Despite the deviations from the plan, the restored stream channel has proven stability and resistance to peak flows, with only marginal traces of the spontaneous evolution of the channel. The analysis of the extent of the flood spill during the flash flood in June 2017 indicated that the restored meandering channel of the watercourse is able to capture the flood event corresponding to a five-year flood while keeping the water spill inside the riparian zone.

This study proved that the UAV technologies represent a survey tool with unique features, applicable for the monitoring of stream restoration projects. The UAV surveys can benefit from the very high resolution of the spatial data, the ability to maintain multitemporal monitoring, and suitability of the data for further quantitative and qualitative analysis. With the operability and cost efficiency of surveys, UAV technology should be considered as a standard survey tool when designing stream restoration monitoring plans.

References

1. Klemas, V. Remote Sensing of Riparian and Wetland Buffers: An Overview. *J. Coast. Res.* **2014**, 869–880.
2. Cordell, S.; Questad, E.J.; Asner, G.P.; Kinney, K.M.; Thaxton, J.M.; Uowolo, A.; Brooks, S.; Chynoweth, M.W. Remote sensing for restoration planning: How the big picture can inform stakeholders. *Restor. Ecol.* **2017**, *25*, S147–S154.
3. Shuman, C.S.; Ambrose, R.F. A Comparison of Remote Sensing and Ground-Based Methods for Monitoring Wetland Restoration Success. *Restor. Ecol.* **2003**, *11*, 325–333.
4. Hestir, E.L.; Khanna, S.; Andrew, M.E.; Santos, M.J.; Viers, J.H.; Greenberg, J.A.; Rajapakse, S.S.; Ustin, S.L. Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. *Remote Sens. Environ.* **2008**, *112*, 4034–4047.
5. Tiner, R.W. Remotely-sensed indicators for monitoring the general condition of "natural habitat" in watersheds: an application for Delaware's Nanticoke River watershed. *Ecol. Indic.* **2004**, *4*, 227–243.
6. Gergel, S.E.; Stange, Y.; Coops, N.C.; Johansen, K.; Kirby, K.R. What is the Value of a Good Map? An Example Using High Spatial Resolution Imagery to Aid Riparian Restoration. *Ecosystems* **2007**, *10*, 688–702.
7. Keeton, W.S.; Copeland, E.M.; Sullivan, S.M.P.; Watzin, M.C. Riparian forest structure and stream geomorphic condition: implications for flood resilience. *Can. J. For. Res.* **2017**, *47*, 476–487.
8. Watanabe, Y.; Kawahara, Y. UAV Photogrammetry for Monitoring Changes in River Topography and Vegetation. *Procedia Eng.* **2016**, *154*, 317–325.
9. Casado, M.R.; Gonzalez, R.B.; Kriechbaumer, T.; Veal, A. Automated Identification of River Hydromorphological Features Using UAV High Resolution Aerial Imagery. *Sensors* **2015**, *15*, 27969–27989.
10. Langhammer, J.; Vacková, T. Detection and Mapping of the Geomorphic Effects of Flooding Using UAV Photogrammetry. *Pure Appl. Geophys.* **2018**, *175*, 3223–3245.
11. Kliment, Z.; Matoušková, M.; Šobr, M.; Potučková, M.; Hujslová, J. Fluvial dynamics and selected methods of ecohydrological monitoring of restored Sviňovicky brook channel. *Acta Universitatis Carolinae-Geographica* **2008**, *43*, 125–144.
12. Eisenbeiss, H. A mini unmanned aerial vehicle (UAV): system overview and image acquisition. *Remote Sens. Spat. Inf. Sci.* **2004**, *36*, 1–7.
13. Flener, C.; Vaaja, M.; Jaakkola, A.; Krooks, A.; Kaartinen, H.; Kukko, A.; Kasvi, E.; Hyyppä, H.; Hyyppä, J.; Alho, P. Seamless mapping of river channels at high resolution using mobile liDAR and UAV-photography. *Remote Sens.* **2013**, *5*, 6382–6407.

14. Turner, D.; Lucieer, A.; Watson, C. An Automated Technique for Generating Georectified Mosaics from Ultra-High Resolution Unmanned Aerial Vehicle (UAV) Imagery, Based on Structure from Motion (SfM) Point Clouds. *Remote Sens.* **2012**, *4*, 1392–1410.

15. Miřijovský, J.; Langhammer, J. Multitemporal Monitoring of the Morphodynamics of a Mid-Mountain Stream Using UAS Photogrammetry. *Remote Sens.* **2015**, *7*, 8586–8609.

16. Tamminga, A.D.; Eaton, B.C.; Hugenholtz, C.H. UAS-based remote sensing of fluvial change following an extreme flood event. *Earth Surf. Processes Landforms* **2015**, *40*, 1464–1476.

17. Tamminga, A.; Hugenholtz, C.; Eaton, B.; Lapointe, M. Hyperspatial Remote Sensing of Channel Reach Morphology and Hydraulic Fish Habitat Using an Unmanned Aerial Vehicle (UAV): A First Assessment in the Context of River Research and Management. *River Res. Appl.* **2015**, *31*, 379–391.

18. DeBell, L.; Anderson, K.; Brazier, R.E.; King, N.; Jones, L. Water resource management at catchment scales using lightweight UAVs: Current capabilities and future perspectives. *J. Unmanned Veh. Sys.* **2015**, *4*, 7–30.

19. Van Iersel, W.K.; Straatsma, M.W.; Addink, E.A.; Middelkoop, H. Monitoring phenology of floodplain grassland and herbaceous vegetation with UAV imagery. In Proceedings of the XXIII ISPRS Congress, Commission VII, Prague, Czech Republic, 12–19 July 2016; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2016; Volume 41, pp. 569–571.

20. Rusnák, M.; Sládek, J.; Kidová, A.; Lehotský, M. Template for high-resolution river landscape mapping using UAV technology. *Measurement* **2018**, *2018*, 139–151.

21. Mathias Kondolf, G.; Micheli, E.R. Evaluating stream restoration projects. *Environ. Manag.* **1995**, *19*, 1–15.

22. Bernhardt, E.S.; Palmer, M.A. Restoring streams in an urbanizing world. *Freshw. Biol.* **2007**, *52*, 738–751.

23. Walsh, C.J.; Roy, A.H.; Feminella, J.W.; Cottingham, P.D.; Groffman, P.M.; Morgan, R.P. The urban stream syndrome: current knowledge and the search for a cure. *J. North Am. Benthol. Soc.* **2005**, *24*, 706–723.

24. Brown, K.B. *Urban Stream Restoration Practices: An Initial Assessment*; The Center for Watershed Protection: Ellicott City, MD, USA, 2000.

25. Kopp, J.; Frajer, J.; Pavelková, R. Driving Forces of The Development of Suburban Landscape – A Case Study of The Sulkov Site West of Pilsen. *Quaestiones Geographicae* **2015**, *34*, 51–64.

26. Xia, T.; Zhu, W.; Xin, P.; Li, L. Assessment of urban stream morphology: An integrated index and modelling system. *Environ. Monit. Assess.* **2010**, *167*, 447–460.

27. Palmer, M.A.; Bernhardt, E.S.; Allan, J.D.; Lake, P.S.; Alexander, G.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.N.; Follstad Shah, J.; et al. Standards for ecologically successful river restoration. *J. Appl. Ecol.* **2005**, *42*, 208–217.

28. Miller, J.R.; Craig Kochel, R. Assessment of channel dynamics, in-stream structures and post-project channel adjustments in North Carolina and its implications to effective stream restoration. *Environ. Earth Sci.* **2010**, *59*, 1681–1692.

29. Saldi-Caromile, K.; Bates, K.; Skidmore, P.; Barenti, J.; Pineo, D. *Stream habitat restoration guidelines: Final draft*. Co-published by the Washington Departments of Fish and Wildlife and Ecology and the US Fish and Wildlife Service: Olympia, WA, USA, 2004.

30. Henne, S.K. "New Wilderness" as an Element of the Peri-Urban Landscape. In *Wild Urban Woodlands*; Springer: Berlin/Heidelberg, Germany, 2005; pp. 247–262, ISBN 9783540239123.

31. Kowarik, I. Urban wilderness: Supply, demand, and access. *Urban For. Urban Green.* **2018**, *29*, 336–347.

32. Prague. Prague-10 years of revitalization projects in Prague. Available online: http://www.praha-priroda.cz/priloha/5204e1ef6b232/2017-katalog-potoky-eng-nahled-599e679f08c09.pdf (accessed on 20 January 2018).

33. Fryč, T.; Zusková, I. Assessment of extreme rainfall in SW part of Prague 29.6.2017. *CHMI Inf.* **2017**. (In Czech)

34. DJI Inspire 1 Pro User Manual v1.0. Available online: https://www.dji.com/cz/inspire-1-pro-and-raw (accessed on 5 January 2017).

35. DJI. DJI Phantom 2 Vision+. Available online: https://www.dji.com/phantom-2-vision-plus/info (accessed on 13 July 2018).

36. Fonstad, M.A.; Dietrich, J.T.; Courville, B.C.; Jensen, J.L.; Carbonneau, P.E. Topographic structure from motion: a new development in photogrammetric measurement. *Earth Surf. Processes Landforms* **2013**, *38*, 421–430.

37. M.W. Smith; J.L. Carrivick; D.J. Quincey Structure from motion photogrammetry in physical geography. *Prog. Phys. Geogr.* **2015**, *40*, 247–275.

38. Langhammer, J.; Lendzioch, T.; Miřijovský, J.; Hartvich, F. UAV-Based Optical Granulometry as Tool for Detecting Changes in Structure of Flood Depositions. *Remote Sens.* **2017**, *9*, 240.

39. Agisoft Agisoft PhotoScan User Manual. Available online: http://www.agisoft.com/ (accessed on 1 October 2017).

40. van Rees, E. Creating Aerial Drone Maps Fast. *GeoInformatics* **2015**, *18*, 24–25

41. Melville, J.K.; Martz, L.W. A Comparison of Data Sources for Manual and Automated Hydrographical Network Delineation. *Canadian Water Res. J. Revue Canadienne des Res. Hydriques* **2004**, *29*, 267–282.

42. Leckie, D.G.; Cloney, E.; Jay, C.; Paradine, D. Automated Mapping of Stream Features with High-Resolution Multispectral Imagery. *Photogrammetr. Eng. Remote Sens.* **2005**, *71*, 145–155.

43. Heine, R.A.; Lant, C.L.; Sengupta, R.R. Development and Comparison of Approaches for Automated Mapping of Stream Channel Networks. *Ann. Assoc. Am. Geogr.* **2004**, *94*, 477–490.

44. Chiang, Y.-Y.; Leyk, S.; Knoblock, C.A. Efficient and Robust Graphics Recognition from Historical Maps. In Proceedings of the Graphics Recognition. New Trends and Challenges; Springer: Berlin/Heidelberg, Germany, 2013; pp. 25–35.

45. Al-Douri, B.A.T.; Al-Khaffaf, H.S.M.; Talib, A.Z. Empirical Performance Evaluation of Raster to Vector Conversion with Different Scanning Resolutions. In Proceedings of the Visual Informatics: Sustaining Research and Innovations, Selangor, Malaysia, 9–11 November 2011; Springer: Berlin/Heidelberg, Germany, 2011; pp. 176–182.

46. Williams, G.P. River meanders and channel size. *J. Hydrol.* **1986**, *88*, 147–164.

47. Clerici, A.; Perego, S. A set of GRASS GIS-based Shell scripts for the calculation and graphical display of the main morphometric parameters of a river channel. *Int. J. Geosci.* **2016**, *7*, 135–143.

48. Park, J. Review on remote sensing data-based stream mapping algorithms. *Forest Sci. Technol.* **2013**, *9*, 87–96.

49. Jensen, A.M.; Hardy, T.; McKee, M. Using a multispectral autonomous unmanned aerial remote sensing platform (AggieAir) for riparian and wetlands applications. *Geosci. Remote* **2011**, doi:10.1109/IGARSS.2011.6049953

50. Džubáková, K.; Molnar, P.; Schindler, K.; Trizna, M. Monitoring of riparian vegetation response to flood disturbances using terrestrial photography. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 195–208.

51. Minařík, R.; Langhammer, J. Use of a Multispectral UAV Photogrammetry for Detection and Tracking of Forest Disturbance Dynamics. In Proceedings of the XXIII ISPRS Congress, Commission VII, Prague, Czech Republic, 12–19 July 2016; International Society for Photogrammetry and Remote Sensing: Hannover, Germany, 2016; Volume XLI-B8.

52. Sankey, T.; Donager, J.; McVay, J.; Sankey, J.B. UAV lidar and hyperspectral fusion for forest monitoring in the southwestern USA. *Remote Sens. Environ.* **2017**, *195*, 30–43.

53. Conrad, O.; Bechtel, B.; Bock, M.; Dietrich, H.; Fischer, E.; Gerlitz, L.; Wehberg, J.; Wichmann, V.; Böhner, J. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. *Geosci. Model Dev.* **2015**, *8*, 1991–2007.

54. Xiang, M.; Hung, C.-C.; Pham, M.; Kuo, B.-C.; Coleman, T. A parallelepiped multispectral image classifier using genetic algorithms. In Proceedings of the 2005 IEEE International Geoscience and Remote Sensing Symposium, Seoul, Korea, 29 July 2005.

55. Hammersmark, C.T.; Dobrowski, S.Z.; Rains, M.C.; Mount, J.F. Simulated Effects of Stream Restoration on the Distribution of Wet-Meadow Vegetation. *Restor. Ecol.* **2010**, *18*, 882–893.

56. Xue, J.; Su, B. Significant Remote Sensing Vegetation Indices: A Review of Developments and Applications. *J. Sensors* **2017**, *2017*, 1353691.

57. Gitelson, A.A.; Kaufman, Y.J.; Stark, R.; Rundquist, D. Novel algorithms for remote estimation of vegetation fraction. *Remote Sens. Environ.* **2002**, *80*, 76–87.

58. Motohka, T.; Nasahara, K.N.; Oguma, H.; Tsuchida, S. Applicability of Green-Red Vegetation Index for Remote Sensing of Vegetation Phenology. *Remote Sens.* **2010**, *2*, 2369–2387.

59. Roth, L.; Streit, B. Predicting cover crop biomass by lightweight UAS-based RGB and NIR photography: an applied photogrammetric approach. *Precis. Agric.* **2018**, *19*, 93–114.

60. Lussem, U.; Bolten, A.; Gnyp, M.L.; Jasper, J.; Bareth, G. Evaluation of RGB-based vegetation indices from UAV imagery to estimate forage yield in grassland. *ISPRS-Int. Arch. Photogram., Remote Sens. Spat. Inf. Sci.* **2018**, 1215–1219.

61. Riley, A.L. *Restoring Streams in Cities: A Guide for Planners, Policymakers, and Citizens*; Island Press: Washington, D.C., WA, USA, 1998; ISBN 9781610913539.

62. Weiss, A.; Matouskova, M.; Matschullat, J. Hydromorphological assessment within the EU-Water Framework Directive—Trans-boundary cooperation and application to different water basins. *Hydrobiologia* **2007**, *603*, 53–72.

63. Simon, A.; Bennett, S.J.; Castro, J.M. *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*; John Wiley & Sons: Hoboken, NJ, USA, 2013; ISBN 9781118671788.

64. Koepke, J. Urban Stream Restoration and Applied Practices in Northeast Illinois. *J. Green Build.* **2017**, *12*, 13–27.

65. Langhammer, J.; Bernsteinova, J.; Mirijovsky, J. Building a High-Precision 2D Hydrodynamic Flood Model Using UAV Photogrammetry and Sensor Network Monitoring. *Water* **2017**, *9*, 861.

66. Brázdil, K. *Technical Report to the 5th Generation Digital Terrain Model (DMR 5G)*; CUZK: Prague, Czech Republic, 2016.

67. Meng, X.; Shang, N.; Zhang, X.; Li, C.; Zhao, K.; Qiu, X.; Weeks, E. Photogrammetric UAV Mapping of Terrain under Dense Coastal Vegetation: An Object-Oriented Classification Ensemble Algorithm for Classification and Terrain Correction. *Remote Sens.* **2017**, *9*, 1187.

68. Müllerová, J.; Bartaloš, T.; Brůna, J.; Dvořák, P.; Vítková, M. Unmanned aircraft in nature conservation: an example from plant invasions. *Int. J. Remote Sens.* **2017**, *38*, 2177–2198.

69. Fryskowska, A.; Kedzierski, M.; Grochala, A.; Braula, A. CALIBRATION OF LOW COST RGB AND NIR UAV CAMERAS. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2016**, *XLI-B1*, 817–821.

70. Rasmussen, J.; Ntakos, G.; Nielsen, J.; Svensgaard, J.; Poulsen, R.N.; Christensen, S. Are vegetation indices derived from consumer-grade cameras mounted on UAVs sufficiently reliable for assessing experimental plots? *Eur. J. Agron.* **2016**, *74*, 75–92.

71. Belletti, B.; Rinaldi, M.; Buijse, A.D.; Gurnell, A.M.; Mosselman, E. A review of assessment methods for river hydromorphology. *Environ. Earth Sci.* **2014**, *73*, 2079–2100.

72. Rubin, Z.; Kondolf, G.; Rios-Touma, B. Evaluating Stream Restoration Projects: What Do We Learn from Monitoring? *Water* **2017**, *9*, 174.