Remote Sensing of Visible Dye Concentrations During a Tracer Experiment on a Large, Turbid River

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Abstract Understanding dispersion in rivers is critical for numerous applications, such as characterizing larval drift for endangered fish species and responding to spills of hazardous materials. Injecting a visible dye into a river can yield insight on dispersion processes, but conventional field instrumentation yields limited data on variations in dye concentration over time at a few, fixed points. Remote sensing can provide more detailed, spatially distributed information on the dye's motion, but this approach has only been tested in clear-flowing streams. The purpose of this study was to assess the potential of remote sensing to facilitate tracer studies in more turbid rivers. To pursue this objective, we injected Rhodamine WT dye into the Missouri River and collected field spectra from a boat, videos from a small unoccupied aircraft system (sUAS), and orthophotos from an airplane. Applying an optimal band ratio analysis (OBRA) algorithm to the field spectra revealed strong correlations ($R^2 = 0.936$) between a spectrally based quantity and in situ concentration measurements. OBRA also performed well for broadband RGB (red, green, blue) images extracted from the sUAS-based videos; the resulting concentration maps were used to produce animations that captured movement of the dye pulse. Spectral mixture analysis of repeat orthophoto coverage yielded relative concentration estimates that provided a synoptic perspective on dispersion of the dye throughout the entire 13.8 km reach over the full 2.5-hr duration of the experiment. The results of this study demonstrate the potential to remotely sense tracer dye concentrations in large, highly turbid rivers.

Plain Language Summary The movement of organisms and contaminants through a river system is influenced by flow patterns within the channel. Understanding the dispersion processes that create these patterns can facilitate a number of important applications, including predicting travel times for spills of toxic materials and simulating larval drift for endangered species of fish. An effective and intuitive means of examining dispersion are to conduct a tracer experiment by injecting a visible dye into a river and then measuring changes in dye concentration over time. Typically, these data are collected by sensors deployed at a few, fixed monitoring locations, but this approach yields only limited insight. Remote sensing methods, in contrast, can provide more detailed, spatially distributed information on the dye's movement along and across the channel, at least in the clear-flowing streams examined through previous research. This study demonstrated the potential to estimate tracer dye concentrations in a large, turbid river from various types of remotely sensed data, including field spectra from a boat, videos from a small unoccupied aircraft system, and digital photography from an aircraft. This approach could be used to characterize flow patterns to support conservation of endangered fish such as the pallid sturgeon along the Missouri River and its tributaries.

1. Introduction

The motion of a small organism, a contaminant, or any other suspended or dissolved constituent through a river system is influenced by the spatial organization of the flow field. Understanding how materials are redistributed by various dispersion processes is thus critical for a broad range of applications. For example, numerical dispersion models are often used to simulate the spread of pollutants and other dangerous substances. This approach can inform disaster response by predicting how a spill of oil or hazardous waste will spread along and across a river, providing travel time estimates, and highlighting locations where contaminants might accumulate and pose a persistent environmental hazard. This kind of information is critical for emergency management agencies tasked with issuing public health advisories and leading containment and remediation activities following a spill (e.g., Nelson et al., 2018; Seo et al., 2016). Similarly, in a biological context, characterizing the onset, growth, and movement of harmful algal blooms could yield insight regarding their adverse effects on aquatic ecosystems and human health (e.g., Brooks et al., 2016; Burford et al., 2020). This study was designed to support ongoing efforts
to conserve endangered pallid sturgeon along the Missouri River (Erwin et al., 2018). More specifically, our objectives were to gain knowledge regarding the dispersion mechanisms that influence the drift of sturgeon larvae and to assess the performance of structures intended to improve rearing habitat by creating low-velocity refugia.

Tracer experiments are a popular and often effective means of examining dispersion processes in open channel flows. These studies involve introducing a substance into the channel and measuring how its concentration changes over time as the material spreads both downstream and in the transverse direction. Visible dyes are frequently used for this purpose, with Rhodamine WT (RWT) being perhaps the most common. This type of dye can be treated as a conservative tracer for most surface water applications where groundwater flow and hyporheic exchange are not significant and sorption of RWT to sediment can be considered negligible (Runkel, 2015). Typically, submersible fluorometers, also known as sondes, are used to measure RWT concentrations in situ at a fixed number of sparsely distributed, stationary monitoring locations. This approach provides detailed information on changes in concentration over time as dye drifts past an instrument, leading to a so-called breakthrough curve. Sonde observations can be used to evaluate one-dimensional (1D) dispersion models that predict how concentrations vary along a channel and thus provide travel time estimates. Although these models can help to inform large-scale forecasts for long river segments, the output from a 1D model is averaged across the channel and cannot represent the lateral concentration gradients, eddies, and localized flow patterns that are of greater interest for many smaller-scale applications (Baek et al., 2019). Enhanced spatial detail is often critical for biological investigations, where two-dimensional (2D) dispersion models and various particle-tracking algorithms are increasingly used to provide higher resolution not only along but also across the channel (e.g., McDonald & Nelson, 2020). In addition, the logistical constraints and cost associated with deploying in situ fluorometers, particularly in large rivers, imply that this type of instrumentation cannot be used to characterize the complex spatial patterns of dispersion that develop rapidly when a pulse of dye is released into the channel instantaneously at a single injection point.

Remote sensing provides an appealing alternative that could facilitate dispersion studies by circumventing some of the obstacles that tend to impede conventional field-based investigations. For example, inferring dye concentrations from images could provide the spatially distributed, detailed data needed to resolve subtle but ecologically significant small-scale features of the flow field and to refine 2D models. A strong precedent for remote sensing of dispersion patterns was initially established in a coastal setting. Clark et al. (2014) demonstrated that passive optical image data could be used to estimate RWT concentrations and applied this approach to identify eddies and other small-scale structures in the surf zone from both a relatively simple two-band camera and a more sophisticated hyperspectral imaging system. This study also elucidated the physical basis for inferring dye concentrations from observations of water color: reflectance in green wavelengths from 530 to 570 nm decreases due to absorption by RWT whereas the presence of RWT tends to increase reflectance in longer red and near-infrared (NIR) wavelengths from 570 to 750 nm. Moreover, RWT has known fluorescent properties, with an excitation band at 557 nm and an emission band at 582 nm (Viriot & Andre, 1989). Although the absorption and reflectance spectra of RWT thus overlap around 570 nm, Clark et al. (2014) showed that the ratio of the upwelling spectral radiance (proportional to the brightness of an image pixel) in a green absorption band to that recorded at a reflectance peak in the red portion of the spectrum was highly correlated with in situ observations of RWT concentration. Similarly, Burdziakowski et al. (2021) used red, green, blue (RGB) images acquired from a small unoccupied aircraft system (sUAS) deployed above a bay to map dispersion of RWT and fluorescein, another greenish yellow-hued visible dye. Powers et al. (2018) also used data from an sUAS to characterize diffusion of a pulse of fluorescein injected into a small inland reservoir. In a recent coastal application, Filippi et al. (2021) collected water samples from an sUAS and reported moderate correlations between the RWT concentrations in these samples and band ratios calculated from color images acquired from the sUAS at the same time.

The potential to remotely sense tracer dye concentrations in river systems was demonstrated through a pair of recent studies. Baek et al. (2019) performed an experiment to assess the feasibility of inferring RWT concentrations from RGB images acquired by an sUAS deployed above a sinuous outdoor flume. Although variations in water depth and bottom composition modified the relationship between image brightness and dye concentration on a local basis, Baek et al. (2019) trained an artificial neural network to account for these complications and produced accurate concentration maps from RGB data. In addition, Legleiter et al. (2019) pursued a more spectrally explicit approach using images from the same experimental channel examined by Baek et al. (2019) as well as field-based reflectance measurements and various types of image data from a large natural river. An
optimal band ratio analysis (OBRA) algorithm originally developed for estimating water depths (Legleiter & Harrison, 2019; Legleiter et al., 2009) served to identify wavelength combinations yielding strong correlations between a spectrally based quantity and in situ concentration measurements. Relative to the machine learning method employed by Baek et al. (2019), OBRA provided greater insight as to how reflectance varied with concentration and which portions of the spectrum were most sensitive to differences in the amount of RWT. Legleiter et al. (2019) reported very strong \( R^2 \) from 0.94 to 0.99 relationships between log-transformed band ratios and RWT concentrations across a broad range of visible wavelengths for several distinct data sets: sUAS-based hyperspectral images from the experimental flume, field spectra collected from a boat on the Kootenai River, and both hyperspectral images and digital aerial photography acquired along the Kootenai from a fixed-wing aircraft. Moreover, Legleiter et al. (2019) showed that equations relating color to concentrations derived from field spectra could be applied to calibrated hyperspectral images and that RWT concentrations could be estimated nearly as accurately from RGB images as from the hyperspectral data.

Although these two investigations imply that remote sensing could become a powerful tool for examining dispersion patterns in rivers, a critical knowledge gap remains. Whereas the Kootenai is an exceptionally clear river, with a measured turbidity of 1.09 NTU (Legleiter & Fosness, 2019), and the flume used in the experiments of Baek et al. (2019) and Legleiter et al. (2019) was shallow and clear, many rivers of interest are larger, deeper, and far more turbid. The lack of data from sediment-laden waters is problematic because the optical characteristics of the water itself are an important consideration when attempting to infer tracer dye concentrations via remote sensing. For example, the linear relationships between band ratios and RWT levels reported by Clark et al. (2014) were strongest at low concentrations (<20 ppb) but became nonlinear at higher concentrations, with a degree of convexity or concavity that varied as a function of the inherent optical properties of the water column. These properties in turn depend on the amount of suspended sediment, chlorophyll, and dissolved organic matter present within the water (Mobley, 1994). Thus, greater turbidity could undermine remote sensing of dye concentrations because the approach relies upon the change in water color that occurs when a visible tracer is present. However, the reflectance signal associated with the dye could be obscured if the river is already conveying a large volume of suspended sediment that imparts a pronounced background color to the water. These issues motivated a recent study designed to evaluate whether a remote sensing approach might be applied to rivers far more turbid than those examined previously. Legleiter et al. (2020) performed an experiment that involved manipulating RWT concentration and turbidity in two tanks while collecting field spectra and sUAS-based RGB and hyperspectral images. OBRA of these three data sets revealed strong relationships between spectrally based quantities and RWT concentrations for turbidities as high as 60 NTU, within the range of median daily-average turbidity values reported for the Missouri River by Legleiter et al. (2020): 14.7–207 NTU. These results provided further evidence of the potential to infer tracer dye concentrations from remotely sensed data and suggested that this approach could be extended to larger, higher turbidity rivers.

The objective of the investigation described herein was to take the logical next step and directly test the feasibility of mapping dispersion patterns from image data by collecting remotely sensed data during a tracer experiment on the large, turbid Missouri River. In an applied context, the motivation for this study was to provide science support for ongoing efforts to facilitate recovery of endangered pallid sturgeon (Scaphirhynchus albus), with a specific focus on the movement of larvae within the Missouri River and its tributaries (Erwin et al., 2018). Dispersal, in the context of pallid sturgeon larvae, is a biological term that refers to the combined, net effect of both passive dispersion by the ambient flow field and active motion resulting from the organisms’ behavior. Dispersal of early-life-stage sturgeon is a keystone of the species’ life history that could represent a recruitment bottleneck (Jacobson et al., 2016); tracer studies could help ecologists to better understand and model this important process. In addition, detailed, spatially distributed information on small-scale flow patterns in the vicinity of the interception and rearing complexes (IRCs) designed to improve larval rearing habitat could help future studies to assess the extent to which these engineered structures are functioning as intended.

Remote sensing is uniquely capable of providing this kind of information and offers a key advantage over standard field methods: quantitative data on water color acquired from a variety of sensors can be used to infer concentrations of visible tracers like RWT across a broad range of spatial and temporal scales. A particularly powerful approach might involve acquiring data from several different platforms, each providing unique insight on the dispersion processes at work within the river of interest. For example, video from an sUAS could yield a high level of temporal detail for a relatively small area while repeated coverage by a higher-flying fixed-wing aircraft...
could provide a synoptic perspective on a longer reach at several points in time. We explored these possibilities by pursuing the following research objectives:

1. Assess the feasibility of inferring tracer dye concentrations from remotely sensed data in a large, turbid river under natural field conditions
2. Use field spectra and measurements from an in situ fluorometer to develop relationships between RWT dye concentration and reflectance at a point scale on the order of 0.1 m and over a period of 1 s
3. Use videos acquired from an sUAS hovering above the channel to characterize spatial patterns of dye dispersion over time at a subreach scale on the order of 250 m over a period of 20 min
4. Use repeat orthophoto coverage from a fixed-wing aircraft to map the spread of the tracer at a larger reach scale on the order of 14 km over a period of 2.5 hr
5. Establish a methodological framework for remote sensing of tracer dye concentrations to support dispersion modeling on the Missouri and other large, turbid rivers

2. Materials and Methods

The tracer experiment described herein was conducted along the Missouri River on 5 May 2021 and involved injecting RWT dye into the channel and then acquiring in situ observations of dye concentration along with various forms of remotely sensed data. This approach allowed us to evaluate the potential to remotely sense dispersion patterns in a large, turbid river. The images and field measurements we collected are available through a data release by Legleiter et al. (2022).

2.1. Study Area

This study occurred along the Missouri River at Searcy's Bend, located between river miles 176 and 183 (river miles are the conventional measurement of location along the Missouri River with river mile 0 at the confluence of the Missouri River with the Mississippi River near St. Louis, MO) near Columbia, MO (Figure 1). The mean daily streamflow reported for a nearby U.S. Geological Survey (USGS) gaging station (Boonville, Station No. 06909000) on the day of the tracer experiment was 1,648 m³/s (U.S. Geological Survey, 2021). The streamflow was 72% of streamflow that typically exists in April and May during larval sturgeon dispersal. This portion of the river, like most of the lower Missouri, is heavily engineered for navigation purposes. At the streamflow on the day of the tracer experiment, some of the navigation control structures and several midchannel bars were partially emergent or fully exposed. The water surface slope calculated from a longitudinal profile surveyed on the same day as the dye release was 0.000182 and the mean wetted channel width was 403 m, determined by dividing the area of a water mask, digitized from the orthophotos described below, by the reach length, 13.8 km. Turbidity remained steady throughout the experiment and the mean value recorded by seven separate multiparameter sondes was 35.98 ± 2.13 NTU. This level of turbidity was ~30 times greater than that observed on the Kootenai River during the only previous test of the potential to remotely sense tracer dye concentrations in a natural channel of which we are aware (Legleiter et al., 2019) but slightly lower than the range of turbidities (40–60 NTU) examined during our earlier tank experiment (Legleiter et al., 2020). The turbidity observed during the present tracer study was typical of conditions on the Missouri River: median mean daily values recorded at the nearest USGS gage with long-term turbidity data (Hermann, Station No. 06934500; U.S. Geological Survey, 2021) varied by month and ranged from a low of 14.7 NTU in January to a high of 207 NTU in June (Legleiter et al., 2020).

We selected Searcy's Bend for investigation because the section is geomorphologically representative of the engineered river downstream from Kansas City, MO, where larval sturgeon have been collected. The bend is also part of an adaptive management experiment by the Missouri River Recovery Program (Fischenich et al., 2018; U.S. Army Corps of Engineers, 2016) intended to explore how IRCs (a) increase interception of dispersing larvae from the main channel and (b) provide suitable, low-velocity rearing habitat for larvae along the channel margins. Engineered changes to pre-existing navigation structures at Searcy's Bend include notching of wing dikes to create more direct flow paths to channel-marginal habitats (U.S. Army Corps of Engineers, 2016). A key knowledge gap in the design of IRCs, however, is how complex flow fields and macroturbulence affect interception of larvae from the navigation channel. Although hydrodynamic and particle-tracking models have been implemented to evaluate design alternatives, considerable uncertainty regarding the performance of IRCs persists. The
tracer experiment described herein provided a means of validating particle-tracking models and enhancing our understanding of how IRCs operate.

2.2. Tracer Experiment and In Situ Observations of Dye Concentration

The tracer experiment began at 09:00:00 CST, when 87 L of 20% solution RWT, diluted by approximately half, was released into the Missouri River via a pump system with tubing positioned at the water surface. No attempt
was made to mix the dye vertically because for remote sensing purposes we were only interested in dye concentrations at the surface. The dye was injected from two boats as they traveled in opposite directions from the channel centerline toward either bank. This injection transect was located at river mile 182.7, oriented perpendicular to the primary flow direction, and spanned the full channel width. The dye was pumped into the river at the same, steady rate from both boats to provide an even initial distribution of dye from bank to bank. Because each boat required a finite amount of time to transit from the middle of the channel to the bank, the dye pulse was not truly instantaneous but was as close to that ideal objective as was practicable; the injection was completed within 90 s of initiation. Once the dye was introduced in this manner, the remainder of the experiment focused on documenting its dispersion along the river using both in situ instrumentation and remotely sensed data.

We made direct measurements of RWT concentration and turbidity using a set of Turner C3 submersible fluorometers (Turner Designs, 2021), also known as sondes. These instruments measured dye concentration as a function of fluorescence and were calibrated prior to deployment using a two-point (RWT: 0 and 10 ppb; turbidity: 0 and 250 NTU) procedure established by Turner Designs (2021). The calibration of each fluorometer was subsequently tested using a two-point test (RWT: 1 and 30 ppb; turbidity: 100 and 400 NTU). To create calibration and test solutions for fluorescence and turbidity, manufacturer-recommended standards were diluted in distilled water. If the test measurements deviated >5% from the test solution, the instrument was recalibrated and retested.

The sondes were deployed at seven fixed monitoring installations distributed throughout the reach as shown in Figure 1. Each sonde was attached to a buoy whose position was established using a Trimble R2 real-time kinematic global navigation satellite system (GNSS) receiver. Six of the sondes were located along the main channel, at distances from 2.8 to 7.3 km downstream of the injection transect, and one sonde was placed at the downstream end of the side channel on the right side (while facing downstream, west in this case) of Tadpole Island, along the inner bank of Searcy's Bend.

The logging interval for sondes 1, 2, 5, 6, and 7 was set to 30 s, but sondes 3 and 4 were located within the footprint of the sUAS-based videos described below and were thus programmed to make more frequent observations, once every 5 s, to provide the data needed to calibrate image-based concentration estimates. Similarly, an eighth Turner C3 with a 1 s logging interval was deployed on the boat from which field spectra were acquired during several transects back and forth across the channel. Measurements from this sonde were used to relate spectral reflectance to RWT concentration.

All of the instruments were synchronized to allow the in situ and remotely sensed data sets to be linked to one another based on time stamps. The sonde data were postprocessed and smoothed by removing the background fluorescence, identifying and eliminating spikes, and applying a five-point running mean. Breakthrough curves of dye concentration versus time since release for the seven sondes positioned at fixed monitoring locations throughout the reach are plotted in Figure 2. Because this portion of the Missouri River is used as a shipping channel, safety and logistical concerns constrained the placement of each sonde. For this reason, we could not position sonde 1 in the thalweg and as a result, this sensor did not record the maximum concentration of the dye plume, even though sonde 1 was located farthest upstream and closest to the dye release transect. Similarly, sonde 5 was strategically placed immediately downstream of the IRC to provide detailed observations of the flow and dispersion processes operating within this engineered structure. The dye slowed considerably as it moved through the IRC, which resulted in a delayed peak for sonde 5, ~15 min later than sonde 7 even though sonde 7 was located farther downstream.

### 2.3. Field Spectra

The physical basis for remote sensing of a visible tracer dye is a relationship between concentration and the amount of radiant energy due to both reflectance and fluorescence. Under daylight conditions and without a separate light source at the excitation wavelength of the dye, we assumed that the contribution from fluorescence was minimal relative to that from reflectance. To establish such a relation, we obtained direct, field-based measurements of spectral reflectance concurrent with in situ observations of RWT dye concentration. Although the sondes measured RWT concentrations ~30 cm below the water surface, we assumed that these observations were representative of concentrations at the surface. The field spectra and RWT concentration measurements were acquired from a boat using an Analytical Spectral Devices HandHeld2 Pro spectroradiometer (ASD, 2021), which we refer to as the ASD, and the fluorometer described above. A fore-optic connected to the ASD by a
A waterproof cable was mounted on a boom extending out over the water. The instrument was controlled by a laptop on the boat, which allowed the operator to view the spectra in real time as they were acquired. At a typical height of 1 m above the water surface, orienting the 5° fore-optic at nadir yielded a field of view ∼15 cm in diameter. When necessary, the boom was rotated horizontally to avoid shadows cast by the boat. Any effect of the boat propellers was minimal because reflectance measurements were always made upstream and in front of the boat so as to avoid disturbing the water surface and the reflectance therefrom. Field spectra spanning the wavelength range from 400 to 900 nm with a 1 nm sampling interval were collected in reflectance mode based on a white reference established by measuring a Spectralon diffuse reflectance standard (Labsphere, 2021). Dividing the raw digital counts for each water spectrum by the digital counts for the Spectralon panel measurement closest in time yielded relative reflectance spectra in units of percent. This calibration process also involved closing the ASD’s internal shutter to define a dark current correction and was performed at least once every 10 min.

Field spectra and RWT concentration were recorded as the boat traveled back and forth across the channel along a transect 2.5 km downstream from the injection transect (Figure 1). Making repeated passes might have increased mixing of the dye as it passed the boat, but our direct, visual field observations during these transects indicated that the dye was laterally well-mixed at this location along the channel. We therefore assumed that any additional mixing related to the slow movement of the boat across the channel during data collection was negligible relative to the mixing driven by natural macroturbulence within the reach. Although we made a total of 10 passes, some of the data were collected before the dye plume arrived and some after RWT concentrations had returned to negligible levels. In addition, a problem with the white reference for the fourth transect precluded the use of data from that traverse. For these reasons, we retained only observations from transects 3, 5, 6, and 7 for further analysis. For data collection from the moving boat, the ASD saved a spectrum to disk every 3 s while the sonde logged a concentration every second. Each spectrum recorded was the average of five nearly instantaneous measurements separated only by the ASD’s integration time, which remained consistent at 136 ms. The time stamp for each ASD file was used to link the spectrum to the RWT concentration measured at that time. The concentration data used for this analysis were processed as described above. Similarly, the field spectra were smoothed by applying a third-order Savitzky-Golay filter with a 15 nm window two times, consistent with the data processing workflow used in our preliminary tank experiment (Legleiter et al., 2020).

![Breakthrough curves for in situ fluorometers (sondes)](image)

**Figure 2.** Breakthrough curves of dye concentration versus time since release for the seven in situ fluorometers (sondes) placed at the fixed monitoring locations indicated in Figure 1.
Figure 3, which displays the reflectance measurements corresponding to the deciles of the distribution of RWT concentrations observed during this traverse across the channel.

2.4. Spectrally Based Inference of Dye Concentrations

To explore the relationship between reflectance and concentration critical to remote sensing of a visible tracer, we used a spectrally based technique originally developed for mapping river bathymetry (Legleiter & Harrison, 2019; Legleiter et al., 2009) but more recently adapted to infer dye concentrations in both a natural channel (Legleiter et al., 2019) and a controlled experiment (Legleiter et al., 2020). More specifically, to identify and exploit specific wavelengths where reflectance is sensitive to variations in RWT concentration, we performed OBRA. This method involved calculating the log-transformed band ratio $X$ as

$$X = \ln \left( \frac{R(\lambda_1)}{R(\lambda_2)} \right),$$

where $R(\lambda)$ denotes the reflectance at wavelength $\lambda$, for all possible combinations of numerator $\lambda_1$ and denominator $\lambda_2$ wavelengths. The resulting $X$ values were used to perform a separate regression of $X$ against the corresponding in situ measurements of RWT concentration, denoted by $C$, for each of the $\frac{n^n}{n!}$ band combinations, where $n$ is the number of wavelengths and $!$ denotes the factorial operation. The optimal band ratio was then defined as that which yielded the highest coefficient of determination ($R^2$). The resulting regression equation also served as a calibrated relation for inferring $C$ from a spectrally based quantity $X$ derived from field spectra or any other form of remotely sensed data. In addition, the OBRA output was used to visualize spectral variations in the strength of the correlation between $X$ and $C$. The $R^2$ values for all band combinations were organized into matrices and illustrated via two-dimensional plots with the numerator wavelength on the vertical axis, the denominator wavelength on the horizontal axes, and colors representing the $R^2$ value.

Figure 3. Field spectra for deciles of the distribution of dye concentrations measured on a transect across the Missouri River. Each line represents a different concentration decile, with the values listed in the legend in units of ppb.
2.5. Videos Acquired From sUAS

To obtain detailed, spatially distributed information on dispersion of the dye pulse for a 250-m-long subset of the study reach that encompassed some of the dikes comprising the IRC, we acquired a series of videos from sUAS deployed above the area indicated by the yellow polygon in Figure 1. In total, 38 videos, typically 5.5 min in length spanning the entire duration of the tracer experiment, were obtained using two Parrot Anafi sUAS (Parrot, 2021) that together provided continuous coverage, with one in flight while the other was recharged. Four of these videos were sufficient to capture the initial arrival and primary passage of the dye pulse. The Anafis hovered in a fixed position ~365 m above the river, which resulted in a ground sampling distance (i.e., pixel size) of 10 cm. The sUAS were equipped with high dynamic range video cameras that recorded 4K Cinema 4,096 × 2,160-pixel video at a native frame rate of 24 Hz in an MP4 format.

Every 120th frame was extracted from the original videos to match the 5 s sampling interval of the two sondes used to measure RWT concentrations within the footprint of the videos. To account for motion of the sUAS platform during video acquisition, the raw frames were stabilized using the TrakEM2 plugin (Cardona et al., 2012) to the Fiji image processing software package (Fiji, 2021). The average residual displacement following stabilization was <1 pixel for all four videos analyzed. An orthophoto of the Missouri River study area was then used as a base to geo-reference the first frame of the image sequence. The resulting projective transformation was then applied to the entire sequence to transform all of the images to the same real world coordinate system as the field observations. The spatial footprints of the individual frames were overlain on one another and used to define the area of coverage common to all frames following stabilization. This region of interest was used to crop the images and a channel mask was applied to obtain a stack of coregistered water-only images.

The acquisition time of each frame was calculated from the known start time of the video, the retained frame rate, and the number of frames since the beginning of the sequence. These time stamps were then used to synchronize the sUAS-based image data with the in situ measurements of RWT concentration from the two sondes located within the footprint of the videos. To avoid any uncertainties associated with the GNSS positions of the buoys to which the sondes were attached and/or geo-referencing error, we visually identified the buoys in the images and extracted pixels immediately downstream based on their (row, column) image coordinates. We also applied a 3 × 3 pixel averaging window as a form of spatial smoothing. The resulting RGB pixel values were combined with the RWT concentrations to perform OBRA and thus establish relationships between the color of the images and the amount of dye. These relations were applied to all of the images in each sequence to produce continuous maps of RWT concentration and then compiled into animations for visualizing dispersion of the dye plume, provided as Supporting Information S1.

2.6. Repeat Orthophotography Acquired From a Fixed-Wing Aircraft

As a complement to the sUAS-based videos, which provided detailed information on the movement of the dye but for only a small portion of the study area, a sequence of digital orthophotos encompassing the entire 13.8 km reach also was acquired during the tracer experiment. Repeat coverage was obtained by a flight contractor operating a Leica ADS100 digital mapping camera with four spectral bands: blue, green, red, and NIR. Eight flight lines were flown, beginning 3.5 min after the dye was released and separated by ~20 min. Survey ground control also was acquired by the contractor and combined with information from a GNSS receiver and Inertial Motion Unit onboard the aircraft and a stationary GNSS base station during postprocessing. This workflow involved triangulating and fully orthorectifying the images and mosaicking them into digital orthophotos with a 10 cm ground sampling distance. The data were delivered as a set of 160 tiles (20 for each of the eight flight lines) with a north-south extent of 0.8 km per tile in a four-band GeoTIFF format (Legleiter et al., 2022). Because the original images were pixelated and grainy in appearance, we applied a 5 × 5-pixel Wiener spatial smoothing filter to mitigate this noise. Tiles from the fourth flight line are shown in Figure 1.

2.7. Spectral Mixture Analysis (SMA) of Relative Dye Concentrations

Although the combination of eight flight lines and seven sondes could have provided up to 56 paired observations of reflectance and RWT concentration for OBRA, the data set proved to be inadequate for this purpose. Due to the relatively small volume of dye released into the large, turbid Missouri River and the placement of the sondes within a short reach, visible amounts of dye were only present for a small portion of the orthophoto mosaic for
each flight line and these locations seldom corresponded with the sondes. The resulting small sample size and limited range of concentrations was not sufficient for OBRA or any other regression-based calibration.

Because we were unable to retrieve absolute dye concentrations in this manner, we used an alternative approach to infer relative concentrations of RWT throughout the eight mosaics. SMA is a popular remote sensing technique with a long history of terrestrial applications (e.g., Adams et al., 1993) that has also been used in shallow marine (e.g., Hedley et al., 2004) and fluvial (e.g., Legleiter & Roberts, 2005) environments. In the present context, SMA provided a means of inferring the presence of varying amounts of tracer within an image pixel. The basic premise of SMA is that most pixels consist of some combination of two or more spectrally distinct features, called end members. The reflectance spectrum of a mixed pixel is thus modeled as a weighted linear combination of the spectra for two or more pure end members

\[
R' (\lambda) = \sum_{k=1}^{N} f_k R_k (\lambda) + \varepsilon (\lambda).
\]

Here, \(R' (\lambda)\) is the modeled mixture, \(f_k\) represents the fractional abundance of each of the \(N\) end members, \(R_k (\lambda)\) is the reflectance spectrum for the \(k\)th end member, and \(\varepsilon (\lambda)\) is a wavelength-specific error term. We used a fully constrained least squares algorithm to impose a unit sum constraint on the end member fractions \(f_k\) (Roberts et al., 1998).

For this study, a simple two-end member model was sufficient, as the Missouri River was well represented by a combination of RWT dye and turbid water. To define these end members, we used an orthophoto acquired 4.5 min after the dye was released into the channel to digitize one polygon with essentially pure RWT dye and another representative of the background water. These two polygons and the mean spectra for each end member, obtained by averaging the pixel values within the respective polygons, are shown in Figure 4. RWT had a lower reflectance than turbid water in the blue and green bands but appeared brighter in the red portion of the spectrum, consistent with our visual impression; the two-end members had similar, very low reflectances in the NIR.

The SMA algorithm provided estimates of the fractional abundance of the dye end member within each pixel and was applied to all tiles with appreciable amounts of dye. We interpreted the resulting fraction images as an indication of the concentration of RWT at each location within the channel and at each time since the release

![Figure 4.](image-url)

(a) Orthophoto acquired 00:04:30 after dye release

(b) Missouri River end member spectra
relative to the initial concentration \( C_i \) at the injection transect. This approach thus provided synoptic information on the dispersion of RWT dye throughout the reach at several points in time.

3. Results

3.1. Inferring Tracer Dye Concentrations From Field Spectra

Field spectra acquired from a boat during a transect across the Missouri River illustrated the influence of varying concentrations of RWT dye on reflectance (Figure 3). This traverse captured the initial arrival of the dye pulse and sampled concentrations up to nearly 14 ppb, but many of the spectra were associated with very low levels of RWT. The 10 spectra plotted in Figure 3 correspond to the deciles of the distribution of RWT concentrations measured along this transect. As the amount of RWT increased, the peak reflectance increased from 0.044 to 0.054 and shifted from 582 nm to a slightly longer wavelength of 587 nm. Another notable difference among the spectra for low versus high RWT concentrations was a more abrupt decrease in reflectance with increasing wavelength beyond the peak, expressed as a steeper spectral slope \( \frac{dR(\lambda)\,d\lambda}{R(\lambda)} \) around 600 nm for the spectra corresponding to the 9th and 10th deciles of the dye distribution (i.e., the maroon and red lines in Figure 3).

To systematically examine and ultimately exploit these connections between reflectance and concentration, we performed OBRA using field spectra pooled across four transects. The results of this analysis are summarized in Figure 5: the band ratio identified as optimal was \( R(563)/R(602) \). The numerator wavelength was located on the rising limb approaching the reflectance peak at 582 nm, an area where the spectral slope was much steeper for high RWT concentrations than for background water. Similarly, the denominator band occurred where \( dR(\lambda)\,d\lambda \) was negative coming off the peak but again was steeper for higher levels of RWT. The resulting linear relation between \( X \) and \( C \) was strong (\( R^2 = 0.936 \)) and had a negative slope (Figure 5a). For lower values of \( C \), \( R(563) \) and \( R(602) \), located on opposite sides of the reflectance peak, were similar to one another, leading to band ratio values close to 1, the logarithm of which was 0. For higher concentrations, \( R(563) \) was substantially lower than \( R(602) \), leading to band ratio values <1 and thus negative values of \( X \) after taking the log. Small concentrations of dye thus were associated with small values of \( X \) whereas higher concentrations led to increasingly negative values of \( X \), resulting in an inverse relation between \( X \) and \( C \).

In addition to providing a calibrated relation between \( X \) and \( C \), OBRA also yielded insight on spectral variations in the strength of this relationship. Figure 5b portrays all possible band ratios as a matrix with colors representing the \( R^2 \) value for each \( (\lambda_1, \lambda_2) \) combination. Although 563 and 602 nm were selected as the optimal pair, the extensive red tones in Figure 5b suggest that many other wavelengths also would lead to strong correlations between \( X \) and \( C \). For example, the horizontal swath of warm colors centered on \( \lambda_1 = 560 \) nm indicates that pairing a numerator band around 560 nm with any denominator wavelength up to about 820 nm would lead to an \( R^2 > 0.8 \). Similarly, the vertical swath of red tones centered at \( \lambda_2 = 550 \) nm corresponds to strong \( X \) versus \( C \) relations for any \( \lambda_1 < 550 \) nm. Separating these two regions at \( \lambda_2 = 575 \) nm, and also oriented horizontally at \( \lambda_1 = 575 \) nm, are blue streaks representing band pairs for which \( X \) and \( C \) were essentially uncorrelated. These wavelength combinations correspond to crossover points where the steeply increasing spectra for high RWT concentrations intersect the more gently sloping spectra for background water, leading to nearly equal reflectances for all values of \( C \).
To demonstrate the predictive capability of an OBRA relation such as that depicted in Figure 5, we applied the regression equation to field spectra from each of the four transects to show how RWT concentrations varied across the channel and over time. These spectrally based estimates are shown in Figure 6 along with the RWT concentrations measured in situ by the fluorometer deployed from the same boat. Agreement between the concentrations inferred from the spectra and measured by the sonde was quite strong. The lines representing the two types of data are slightly offset from one another in some cases, most notably for cross-section (XS) #3 (Figure 6a), due to the relative positions of the ASD and the sonde. For XS #3, the boom holding the ASD fore-optic extended out over the more heavily dye-laden water before the sonde, which was located further back on the boat, reached that part of the river. The sequence of four XS also captured the progression of the dye through this portion of the study area. The highest concentrations were observed in the middle of the channel for the first XS (#3) sampled after the pulse arrived. By the time, XS #5–7 were recorded, the plume had passed through the thalweg, where flow

Figure 6. Concentrations of Rhodamine WT (RWT) dye observed along four passes of a cross-section (XS) on the Missouri River compared to the concentrations estimated from field spectra using an optimal band ratio analysis (OBRA) relation developed from the field spectra for each transect. Distances are from the left descending bank (i.e., river left when facing downstream).
velocities were highest, and appreciable concentrations were recorded only near the right bank, where velocities were much lower. By the time, XS #7 was completed, the peak concentrations along the right bank were only a third as high as those observed in the center of the channel during XS #3.

### 3.2. Quantifying Spatial and Temporal Patterns of Tracer Dispersion From sUAS-Based Videos

The essentially continuous field spectra not only revealed a strong relationship between the color of the water and the amount of tracer therein but also implied that sensors with broader bands, including standard RGB cameras, could be used to map dye concentrations. Although such a capacity has been established in experimental settings (Baek et al., 2019; Legleiter et al., 2020) and clear-flowing natural channels (Legleiter et al., 2019), a primary objective of this study was to assess whether this approach might be applied to a large, turbid river. As an initial test, we acquired and processed a series of sUAS-based videos for a portion of the Missouri River as described in Section 2.5.

We extracted RGB pixel values from the resulting image sequences at the locations of sondes 3 and 4, along with the RWT concentrations recorded at the time each frame was captured. Time series of image pixel values extracted from the first video acquired after the initial pulse of dye arrived are plotted in Figure 7 as well as the dye concentrations for both sondes. For sonde #3, located farther upstream, C remained at background levels for the first 1.5 min of the video but began to increase once the dye plume arrived 1 hr, 8 min after the initial release, reaching a concentration of 23 ppb by the end of the video 4 min later. During this period, the blue band pixel values did not appear to vary systematically but the red band became brighter during the last 4 min of the video as the amount of dye present increased. The green band decreased slightly over the final 1.5 min of the video, when the RWT concentration and red band were increasing most rapidly. Sonde #4 was located farther downstream and recorded a more gradual, steady rise to a lower peak concentration of 16 ppb. The green band was brighter than the red band for the first 2.5 min of the video when concentrations were low, similar to the red band for the next 2 min, and then darker than the red band over the last 1.5 min of the video when C was highest.

To convert these trends in image brightness and dye concentration into a quantitative relationship that could be used to map dispersion patterns from the video, we applied the same OBRA algorithm as for the field spectra. Results from the first of the four videos we considered are summarized in Figure 8, which shows a strong correlation ($R^2 = 0.829$) between the image-derived quantity $X$, defined using the G/R band ratio, and RWT concentrations observed in situ. We used a quadratic equation between $X$ and $C$ to account for the curvature evident in Figure 8a. Higher concentrations were associated with brighter pixels in the red band and darker pixels in the green band, leading to G/R ratio values <1 and thus negative values of $X$. For intermediate concentrations, the red and green bands were more similar, leading to $X$ values near 0. For RWT levels near background, the green band tended to be brighter than the red, leading to positive $X$ values and an overall inverse relationship between $X$ and $C$. The OBRA matrix plot in Figure 8b indicates that although the G/R band ratio provided the highest correlation with the measured concentrations, the other two band ratios also would have yielded reasonably strong correlations, with an $R^2$ of 0.761 for B/R and 0.654 for B/G.

Similar analyses also were performed for three subsequent videos; the OBRA output is summarized in Table 1. For the latter three videos, which were acquired after the initial arrival of the dye pulse and thus captured lower RWT concentrations, $X$ versus $C$ correlations were not as strong, with $R^2$ decreasing to 0.342 for the final video we examined. Also noteworthy in Table 1 was the shift from G/R to G/B as the optimal band ratio for the last video.

When the range of concentrations was greater (i.e., from background levels up to 25 ppb); however, more robust $X$ versus $C$ relations were established and applied to each image in a sequence to produce a series of concentration maps. An example from the first frame of the first video analyzed is shown in Figure 9. In this portion of the study reach, a pile of rip-rap located in the middle of the channel just upstream (north) of the video's field of view was emergent above the water surface at this streamflow and diverted the flow to either side. The dye that had been traveling down the river in a symmetric plume along the thalweg was thus split in two, with more of the RWT diverted toward the left (east) bank and a zone of much lower concentrations in the wake of the rip-rap.

To visualize how this pattern evolved over the 5-min duration of the video, we produced similar concentration maps for all subsequent frames and combined them into an animation provided as Movie S1 for this article. This animation revealed that as more of the dye passed by the obstruction in the middle of the river, the plume on the
river left (when facing downstream) side of the channel traveled downstream more rapidly than that on the river right. Some eddying was evident as fluctuations in $C$ over time at a given location, particularly to the right of the centerline. By the midpoint of the video, the two plumes had begun to coalesce and the low-concentration region in the wake of the obstruction disappeared shortly thereafter. The two plumes had converged into a single pulse in the middle of the channel by the end of the sequence, with slightly higher concentrations toward the right bank, opposite the pattern observed at the start of the video. Similar animations were produced from the other videos and are provided as Movies S2–S4.

3.3. Reach-Scale Mapping of Relative Dye Concentrations From Repeat Orthophotography

Dye fraction images derived from orthophotos acquired from an aircraft show the movement of dye along the 13.8-km study reach over a period of 2 hr, 20-min following the release (Figure 10). In producing these maps, we
included only those tiles that contained clearly visible amounts of dye. The first line began within 3.5 min of the release and captured only a small area of very high dye concentrations in the immediate vicinity of the injection transect; this narrow zone of high concentrations was too small to perceive at the scale of the entire reach as depicted in Figure 10. This image was the source of the RWT dye and turbid water end members used to perform SMA (Figure 4). The dye fractions estimated on a per-pixel basis throughout this and all subsequent images were thus interpreted as dye concentrations relative to the initial value $C_0$ associated with the RWT end member. Although the absolute magnitude of $C_0$ was not measured directly, the product of this initial value and the dye fraction $f$ for a given pixel provided a plausible estimate of the relative dye concentration as $fC_0$.

When the aircraft passed over the river for the second time, 24 min after the release, the imaging system captured the pulse of dye as a more extensive, but still highly focused plume centered about 1.33 km downstream of the

Figure 8. Optimal band ratio analysis (OBRA) of RGB (red, green, blue) pixel values extracted from a video acquired by a small unoccupied aircraft system (sUAS) deployed above the Missouri River. (a) Calibration scatter plot for the optimal band ratio. (b) Matrix plot illustrating spectral variations in the strength of the relation between the log-transformed band ratio $X$ and dye concentration for all possible wavelength combinations.
injection transect. The highest relative dye concentrations at this stage of the experiment were on the order of $0.4 C_0$ and the dye was primarily found along the right bank, despite having been injected uniformly across the full width of the channel. The third lap was acquired 43 min after the release and by this time the pulse had taken on a V shape with the leading edge extending farther downstream ($\sim 2.98$ km below the injection site) near the middle of the channel where flow velocities were greatest and a trailing limb on either side.

The dispersion pattern changed considerably in the fourth lap, flown nearly 1 hr, 4 min after the release. By this time, the primary pulse had traveled 4.31 km along the river to the upstream end of Tadpole Island. Encountering this obstruction might have caused the dye to coalesce into a more compact, focused plume in the main channel on the east side of Tadpole Island; downwelling of dye-bearing water and/or upwelling of dye-free water also might have played a role. The relative RWT concentrations in this area were on the order of $0.33 C_0$. Very little dye appeared to enter the Tadpole Chute channel on the west side of Tadpole Island. Also note that the fourth lap was the orthophoto coverage that coincided most closely in time with the sUAS videos described in Section 3.2.

Table 1

| Video   | Postrelease (HH:MM:SS) | $R^2$  | RMSE (ppb) | Numerator band (nm) | Denominator band (nm) | Intercept $a$ (ppb) | Linear term $b$ | Quadratic term $c$ |
|---------|------------------------|--------|------------|---------------------|-----------------------|---------------------|----------------|-------------------|
| P1761560 | 01:06:48               | 0.829  | 2.308      | 650                 | 550                   | 7.261               | 103.969        | 341.320           |
| P1761561 | 01:12:24               | 0.504  | 2.548      | 650                 | 550                   | 15.261              | 110.250        | -179.414          |
| P1761562 | 01:17:59               | 0.596  | 2.962      | 650                 | 550                   | 9.505               | 58.790         | 1730.025          |
| P1701549 | 01:22:24               | 0.342  | 1.395      | 550                 | 450                   | 12.022              | -55.668        | 196.809           |

Note. RMSE = root mean squared error. OBRA relations are quadratic equations of the form $C = a + bX + cX^2$, where $C$ is the concentration of Rhodamine WT (RWT) dye and $X$ is the log-transformed band ratio given by Equation 1 and the latter three columns list the fitted values of the coefficients $a$, $b$, and $c$ for each of the videos.

The dispersion pattern changed considerably in the fourth lap, flown nearly 1 hr, 4 min after the release. By this time, the primary pulse had traveled 4.31 km along the river to the upstream end of Tadpole Island. Encountering this obstruction might have caused the dye to coalesce into a more compact, focused plume in the main channel on the east side of Tadpole Island; downwelling of dye-bearing water and/or upwelling of dye-free water also might have played a role. The relative RWT concentrations in this area were on the order of $0.33 C_0$. Very little dye appeared to enter the Tadpole Chute channel on the west side of Tadpole Island. Also note that the fourth lap was the orthophoto coverage that coincided most closely in time with the sUAS videos described in Section 3.2. For

Figure 9. Example map of Rhodamine WT (RWT) dye concentration derived from a single frame of a video acquired from an sUAS deployed above the Missouri River. The flow direction is to the south, from the top to the bottom of the image. Animated maps produced from each of four separate videos are provided as Supporting Information S1.
the fifth lap, acquired 20 min later, the plume on the east side of Tadpole Island became much more extensive and was most prominent in the middle of the main channel. Locally, more complicated patterns were observed along the margins of the thalweg where the flow interacted with a series of channel control structures and IRCs. These results suggest that the IRC was functioning as intended by adding complexity to the flow field and creating lower velocity areas along the channel margins.

By the time the sixth lap was completed, 1 hr, 42 min after the initial release, most of the dye had traveled downstream beyond Tadpole Island, although smaller amounts lingered in the vicinity of the navigation structures and IRC. An area of relatively high concentrations, on the order of 0.4$C_0$ occurred near the west bank where the channel curved to the east and focused flow toward the outside (east bank) of the bend. A long tail of lower concentrations extended from this primary plume back upstream to the tail of a small midchannel bar. A secondary plume with relative concentrations around 0.23$C_0$ remained in this area. In the seventh lap, the compact plume near the right bank had dispersed and extended further downstream, with the leading edge having crossed over the centerline toward the left bank along with the channel thalweg. An area of moderate relative concentrations persisted at the tail of Tadpole Island where Tadpole Chute rejoined the mainstem. In the eighth and final lap, flown over 2 hr, 23 min following the initial release, the dye had largely dispersed through the study area, with only broad, diffuse areas of low relative concentrations still evident. The lighter blue tones above Tadpole Island for the last three laps are a consequence of an increase in overall image brightness and do not indicate increasing relative dye concentrations in these areas as the experiment went on. Because the water end member used in the SMA was extracted from an image acquired earlier in the day when the sun was less intense, this end member was less representative of images obtained when the sun was higher in the sky. Given the simple two-end member model, the higher reflectance in the later images was accommodated by an increased fractional contribution from the brighter dye end member.

To complement this reach-scale analysis, we also examined a single cross-section extracted from the relative dye concentration maps for flight lines 4–8. This transect was located at the position of sonde #2, ~4.13 km below the injection transect. The resulting sequence of relative concentration cross-sections is illustrated in Figure 11. The leading edge of the dye pulse had reached this location by the time the fourth flight line was acquired, nearly 1 hr, 4 min postinjection, and was focused in the middle of the channel, where the peak relative concentrations were nearly 0.3$C_0$. Secondary peaks, on the order of 0.15$C_0$ were present closer to each bank. Note that the area of 0 relative concentration at 250 m from the left bank present throughout the sequence series occurred where the

![Sequence of relative dye concentration maps](image-url)
transect crossed a rip-rap channel control structure that emerged above the water surface. By the time the next lap was flown, the dye front had passed this section and concentrations had begun to decline. The peak relative concentration during the fifth flight line was <0.2 \( C_0 \) and occurred on the right, rather than the left, side of the channel control structure. For flight lines 6–8, the dye was distributed fairly uniformly across the river with relative dye concentrations between 0.1\( C_0 \) and 0.2\( C_0 \).

Figure 11. Sequence of relative dye concentration transects extracted from dye end member fraction images derived from orthophotos acquired along five flight lines providing repeat coverage of the study reach. The cross-section is located at in situ fluorometer (sonde) #2, positioned near the left bank as shown in Figure 1 (i.e., near the origin of the each transect plotted in this figure). The relative concentration goes to 0 at 250 m from the left bank where the cross-section traverses an exposed bar. Times are listed as hours:minutes:seconds after the dye was released into the river. Distances are from the left descending bank (i.e., river left when facing downstream).
4. Discussion

4.1. Remote Sensing of Tracer Dye Concentrations Across a Range of River Environments

This study complemented previous work on remote sensing of visible tracers in a near-shore coastal setting (Burdziakowski et al., 2021; Clark et al., 2014), an outdoor lab facility (Baek et al., 2019), and a clear-flowing natural river (Legleiter et al., 2019) by evaluating the feasibility of inferring concentrations of RWT dye from passive optical image data in a larger, more turbid river. We also sought to corroborate the experimental finding that the radiancy signal associated with RWT was robust and readily detectable in sediment-laden water with turbidities up to 60 NTU (Legleiter et al., 2020). To pursue this objective, we performed a tracer experiment on the Missouri River, aptly nicknamed the “Big Muddy,” measured RWT concentrations with in situ fluorometers, and acquired field spectra from a boat, RGB video from an sUAS, and orthophotos from a fixed-wing aircraft to quantify the movement of the dye pulse. In aggregate, the results of our field-based investigation demonstrated the ability to characterize dispersion patterns in turbid river channels via remote sensing.

Another important outcome of this study was further evidence of the flexibility and strong performance of the OBRA framework for relating the color of the water to the concentration of dye therein (Legleiter et al., 2019). Whereas Clark et al. (2014) used a prescribed band ratio to link image pixel values to concentrations measured in situ, the primary advantage of OBRA is the ability to identify a pair of bands specific to the water body of interest. Such adaptability is crucial for extending remote sensing of tracer dyes across a range of river environments because the optical properties of the background water can influence the nature and strength of the relationship between reflectance and concentration. For example, although RWT is fluorescent, with excitation and emission peaks at 557 and 582 nm, respectively (Viriot & Andre, 1989), Clark et al. (2014) found that the wavelengths most responsive to increasing dye concentration (553 and 595) did not coincide with these known spectral features. On the exceptionally clear Kootenai River, OBRA of field spectra identified 545 and 595 nm as the optimal band pair, although many other combinations produced correlations that were nearly as strong (Legleiter et al., 2019). The optimal wavelengths varied across the four levels of turbidity tested in our earlier tank study, with the numerator and denominator bands selected tending to be very near one another. For example, for the 40–45 NTU range closest to the turbidity observed on the Missouri River during the present study (35.98 ± 2.13 NTU), the R(545)/R(546) ratio yielded a direct relationship between X and C with an OBRA $R^2$ of 0.986. The field spectra we collected on the Missouri River led to a more widely separated pair of bands, 563 and 602 nm, that exploited differences in spectral slope between high concentrations of RWT and near-background levels and led to an inverse relation between X and C. Given this variability, widely applicable, generic relationships between spectrally based quantities and dye concentrations are likely to remain elusive. The flexibility of OBRA makes this empirical technique well-suited for remote sensing of tracer dye concentrations in river channels, an application that requires local tuning to account for differences in the characteristics of the water, the composition of the streambed in shallow, clear channels, or even the type of dye. However, because OBRA requires field measurements of dye concentration for calibration, the technique might not be appropriate under highly dynamic weather/wind conditions that cause turbidity and other aspects of water quality to change rapidly. In general, if the reflectance data and in situ concentration measurements used to establish the OBRA relation cannot be acquired simultaneously, output from the algorithm might not be reliable.

In cases where the paired observations of reflectance and concentration required to perform OBRA are not available, SMA provides an alternative means of obtaining at least relative estimates of the amount of dye present within each pixel of an image. Close to the point of injection where the tracer is most concentrated, the visual contrast between the dye and the background water is likely to be quite strong, making selection of pure dye and water end members straightforward. Our results suggest that because these two features are so spectrally distinct from one another, a basic two-end member model is sufficient for estimating dye fractions, even for images with only three or four broad spectral bands. Multiplying these fractional abundances, $f$, by the known initial concentration $C_0$, represented by the original dye end member could yield an estimate of the absolute concentration. However, if $C_0$ was not measured directly, as was the case in this study, the product $fC_0$ could still yield plausible estimates of relative dye concentration useful for visualizing dispersion patterns. This spectrally based approach is significant because only three bands are needed to perform a two-end member SMA, implying that this method can be applied to inexpensive, readily available RGB images. Moreover, if relative concentrations are an acceptable output for a given application, the need for in situ instrumentation and careful coordination between field
crews and flight operations is obviated. Removing these technological and logistical barriers is an important step toward wider use of remote sensing to support tracer studies in a variety of river systems.

Our results also highlight the value of employing different forms of remote sensing to characterize dispersion processes across a range of temporal and spatial scales. In this study, we used a spectroradiometer deployed from a boat to obtain essentially instantaneous measurements of reflectance, with a field of view on the order of a few cm, to confirm and quantify the intuitive connection between color and concentration. Legleiter et al. (2019) also showed that an X versus C relation developed from field spectra could be applied to hyperspectral image data, provided that the images are atmospherically corrected and radiometrically calibrated to consistent units of apparent surface reflectance. Although we were not able to fully test this approach on the Missouri River due to a lack of hyperspectral imagery for our study area, the boat-based reflectance data we collected provide an initial proof-of-concept under natural field conditions in a large, turbid river. Moreover, the OBRA results presented herein, as well as those from an earlier tank study (Legleiter et al., 2020), suggest that a high level of spectral detail is not essential and that sensors with broader bands also could yield reliable concentration estimates in this environment. For example, we showed that basic RGB images extracted from an sUAS-based video could be used to accurately retrieve dye concentrations ($R^2 = 0.829$). This type of data has the important advantage of providing high temporal resolution, which we exploited to produce four 5-min animations capturing the arrival and complex evolution of a pulse of RWT dye over an ~250-m-long subset of the reach. Similarly, we used repeat orthophoto coverage to characterize the dye's motion at the scale of the entire 13.8-km-long study area and over the full 2-hr duration of the experiment. For this data set, we used SMA to obtain relative dye concentrations as fractions of the initial concentration at the injection transect, rather than an absolute value in ppb; this approach proved useful for visualizing the dynamics of the dye at these larger scales. By acquiring data from multiple platforms, we demonstrated the potential utility of remote sensing for characterizing dispersion processes in large, turbid rivers in detail across a range of spatial and temporal scales.

4.2. Lessons Learned and Areas of Further Development

Our previous experience on the Kootenai River led to a number of general recommendations for making effective use of remote sensing as an integral component of dispersion studies in rivers. For example, Legleiter et al. (2019) emphasized the need to carefully coordinate field operations with image acquisition, synchronize all data streams to a common time standard, and ensure that in situ observations of dye concentration span the full range of conditions captured by the remotely sensed data. The current study yielded some additional insight to help guide development and applications of this approach. For example, in retrospect, the location of the dye release transect and the volume of RWT we injected into the channel were probably not appropriate, as the pulse rapidly passed by a given location along the river, with the amount of dye quickly returning to background levels. The dye was released ~3.55 km downstream from the Interstate 70 bridge because the dye is highly visible and we wanted to avoid distracting motorists traveling across the bridge during the study. In addition, although introducing a sufficient amount of dye is particularly critical in turbid channels where the water itself has a distinct color that could obscure that associated with the tracer, RWT is costly to obtain and difficult to handle. If given an opportunity to repeat this experiment, along with sufficient resources and no constraints on the location of the dye release transect, we would have introduced a much larger amount of dye at a location further upstream from the IRCs of interest. However, a compromise must be reached between these practical considerations and scientific objectives. Public outreach is another important factor, as the dye is, by design, highly visible and can cause concern for people living, working, or recreating along a river. Securing permissions from local agencies and issuing advisories is thus critical, particularly if a large amount of dye is to be introduced over a long time period.

Another aspect of the investigation we might modify if we were to repeat the experiment would be the placement of in situ fluorometers. For example, for the subset of the reach encompassed by the sUAS-based videos, two of the sondes were strategically positioned within the IRC to provide better understanding of dispersion processes as they relate to pallid sturgeon larval dispersal. One of the sondes was located downstream of a rip-rap control structure in the center of the channel. The flow pattern created by this obstruction dictated that the instrument would capture only moderate concentrations of RWT, whereas much higher amounts of dye flowed past areas to either side of the rip-rap's wake. The second sonde within the video footprint was further downstream and also experienced relatively low concentrations. As a result, we were forced to extrapolate the OBRA relation shown in Figure 8 beyond the range of the in situ calibration data to produce dye maps and animations from the videos. In
addition, our options for sonde placement were constrained by the Missouri River's role as a navigation channel; putting a sensor in the path of a barge or other large vessel would have been risky and was avoided for safety. The tracer experiment on the Missouri River thus provided yet another example of the trade-offs that must be made between achieving the goals of a study and respecting the pragmatic operational issues associated with a particular river environment.

Despite problems of this kind, our investigation demonstrated the ability of remote sensing techniques for mapping dispersion patterns in large, turbid river channels. This research was motivated by the broader objective of better understanding the dispersion processes operating along the Missouri River to help elucidate the physical factors that influence the movement of endangered pallid sturgeon larvae. Another aspect of this effort involves evaluating the performance of projects intended to improve habitat conditions for sturgeon, such as the IRCs recently constructed on Searcy's Bend. Numerical models play a key role in this work and the detailed, spatially distributed information on dispersion patterns obtained via remote sensing could help to validate and refine these models. Whereas in situ fluorometers provide a limited number of concentration time series at individual, isolated points, continuous maps and even animations derived from image data capture subtle variations in dye concentration in two dimensions throughout the reach, which could potentially facilitate model calibration and verification. For example, extracting relative concentration cross-sections from the dye fraction images we produced from the orthophotos, as illustrated in Figure 11, show how the distribution of RWT across the channel evolved over time. This information can be used to calculate lateral dispersion coefficients (e.g., Rypina et al., 2016) that are an important input to numerical models. However, remotely sensed data can only be used to estimate dye concentrations at the water surface, especially in highly turbid rivers like the Missouri where the water column is practically opaque. As a result, an important limitation of remote sensing is that, in and of itself, the approach does not provide information on vertical mixing or flow dynamics and habitat conditions at depth, although a modeled or assumed vertical concentration profile could be used to extrapolate surface concentrations down into the water column. In any case, integrating the wealth of data provided by remote sensing into dispersion models and applying these tools in support of species conservation could provide resource managers and conservationists with a decision-support tool.

5. Conclusion

The purpose of this study was to test the potential to infer concentrations of a visible tracer dye from remotely sensed data in a large river far more turbid than the clear-flowing streams that had been examined previously. To pursue this objective, we conducted a tracer experiment on the Missouri River that involved injecting RWT into the river and then measuring dispersion of the dye along and across the channel using both in situ fluorometers and various forms of passive optical data, including field spectra, videos from an sUAS, and orthophotos from a fixed-wing aircraft. Our analysis of these data led to the following conclusions:

1. Accurate estimates of dye concentration can be inferred from reflectance measurements that quantify water color, even when the water is highly turbid (35.98 ± 2.13 NTU). This result corroborates findings from an earlier experiment that involved manipulating concentration and turbidity in a pair of tanks.

2. Strong correlations ($R^2 = 0.936$) between a spectrally based quantity and dye concentration were derived by applying an OBRA algorithm to essentially continuous field spectra acquired from a boat along four transects across the Missouri River. This empirical technique also performed well ($R^2 = 0.829$) when applied to images with much broader bands acquired using a standard RGB camera deployed from an sUAS.

3. Videos collected from an sUAS were used to produce continuous maps and animations of RWT concentration that captured the arrival and complex evolution of the dye pulse within a 250-m-long subset of the reach over a period of 20 min.

4. Orthophotos acquired along eight repeated flight lines encompassing the entire 13.8-km study area and the full 2.5-hr duration of the experiment provided a synoptic perspective on the movement of the dye. SMA based on two-end members, dye and turbid water, was used to estimate the fractional abundance of RWT within each pixel. These fractions were interpreted as dye concentrations relative to the initial RWT concentration for the dye end member, which was extracted from an image acquired immediately following injection of the dye.

5. The results of this study demonstrated the potential to measure dispersion patterns in large, turbid rivers via remote sensing. Applying this approach to refine numerical models and assess the performance of habitat...
improvement projects could support efforts to conserve endangered pallid sturgeon in the Missouri River and its tributaries.

Data Availability Statement
The data collected for this study are available from https://doi.org/10.5066/P9JDISO3 (Legleiter et al., 2022).

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