Effects of Sensor Resolution on Mapping In-Stream Habitats

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Abstract

Effects of spatial, spectral, and radiometric resolution on remote mapping of fourth-order in-stream habitats were evaluated by comparing hyperspectral imagery to simulated multispectral data. Spectral resolution was more important than spatial or radiometric resolution in improving classification accuracies, although overall accuracies never exceeded 62 percent. Overall accuracies were significantly greater for (1) hyperspectral data (7.2 percent) compared to simulated multispectral imagery, (2) 1-m pixels (4.7 percent) compared to 2.5-m pixels, and (3) 11-bit data (0.8 percent) compared to 8-bit data. Higher spatial resolution also enabled removal of transitional areas between units by using interior buffers, improving accuracy by up to 15.6 percent. We believe low overall accuracies were primarily due to the subjective and oversimplified nature of the polygon-based field maps used as ground reference data, and high-resolution imagery might provide a more detailed representation of in-stream habitats. Improved methods of collecting ground reference data, utilizing a point-based approach, should be developed for assessing the accuracy of classifications derived from fine spatial resolution (less than 5-m) imagery.

Introduction

Streams and riparian zones form the heart of terrestrial ecosystems, often supporting up to half their biodiversity (Karr and Schlosser, 1978), but these narrow ecological lifelines are also vulnerable to natural and anthropogenic disturbances. Various land-use practices can provoke dramatic changes in stream morphology and hydraulic regime, adversely affecting biotic communities dependent upon these factors (Knapp *et al.*, 1998). Classification and mapping of streams is thus crucial for characterizing stream habitats, assessing suitability for different organisms and varying uses, and monitoring the impacts of disturbance on fluvial systems.

Conventional field-based mapping of stream microhabitats such as riffles and pools (Bisson *et al.*, 1982; Ladd *et al.*, 1998) can be time-consuming and expensive, especially when conducted across entire watersheds or on a repeated basis to monitor temporal variation. In addition, traditional field-based mapping is plagued by subjectivity, with a given stream feature classified differently by different surveyors (Marcus, 2002). A compelling need therefore exists to develop a more effective technique for characterizing in-stream habitats. One possible tool is the application of high spatial resolution remote sensing technology to stream classification. This approach potentially provides an objective, quantitative technique driven by the stream's inherent spectral variability.

Aerial photography has been used since the 1940s to document channel changes, but the application of film-based media to fluvial studies at watershed scales has been limited by its spectral range and its restricted spatial and temporal coverage (Wright *et al.*, 2000). Satellite imagery has overcome many of these problems, although most applications have been in larger river systems due to coarse spatial resolution. Nonetheless, remote sensing might be the sole approach capable of generating frequent, synoptic, quantitative data for rivers (Muller *et al.*, 1993; Engman, 1995).

Several recent studies have utilized high spatial resolution digital imagery to quantify and map stream morphology. Five general bottom types were identified with 85 percent accuracy and water depths were measured with 95 percent accuracy on the Saint Mary's River, Michigan, using a 12-band scanner with 10-m resolution (Lyon *et al.*, 1992). In-stream habitats and water depths in the Green River, Utah, were mapped using 0.25- to 3.0-m resolution multispectral video imagery (Hardy *et al.*, 1994), and 1-m resolution scanned panchromatic aerial photos were used to map relative water depths and morphologic features such as riffles and pools on Faith Creek in Alaska (Gilvear *et al.*, 1995). Using simulated nine-band imagery, water depths were estimated with a coefficient of determination (r^2) of 0.67 (Winterbottom and Gilvear, 1997). These previous studies examined rivers larger than the fourth-order mountain stream analyzed in this report.

While the above studies indicate the potential for remote sensing of stream habitats, the use of airborne multispectral imagery has been limited by tradeoffs between spectral resolution and number of spectral bands versus spatial resolution and measurement precision (Price, 1997). Two recent studies highlight the difficulty of selecting the ideal sensor and spatial scale for fluvial applications. Using 1-m, four-band imagery resulted in classification accuracies ranging from 11 to 53 percent for third- and fourth-order in-stream habitats. These poor results were mainly attributed to coregistration errors between ground-based field maps and remote sensing imagery, as well as inadequate spectral separation of habitat types (Wright *et al.*, 2000). In a fifth-order stream, hyperspectral imagery was used to classify four in-stream habitats with overall accuracies of 66 percent and 85 percent for 5-m and 1-m resolution imagery, respectively (Marcus, 2002). Rarely, however, is imagery with both 1-m resolution and hyperspectral band coverage readily available.

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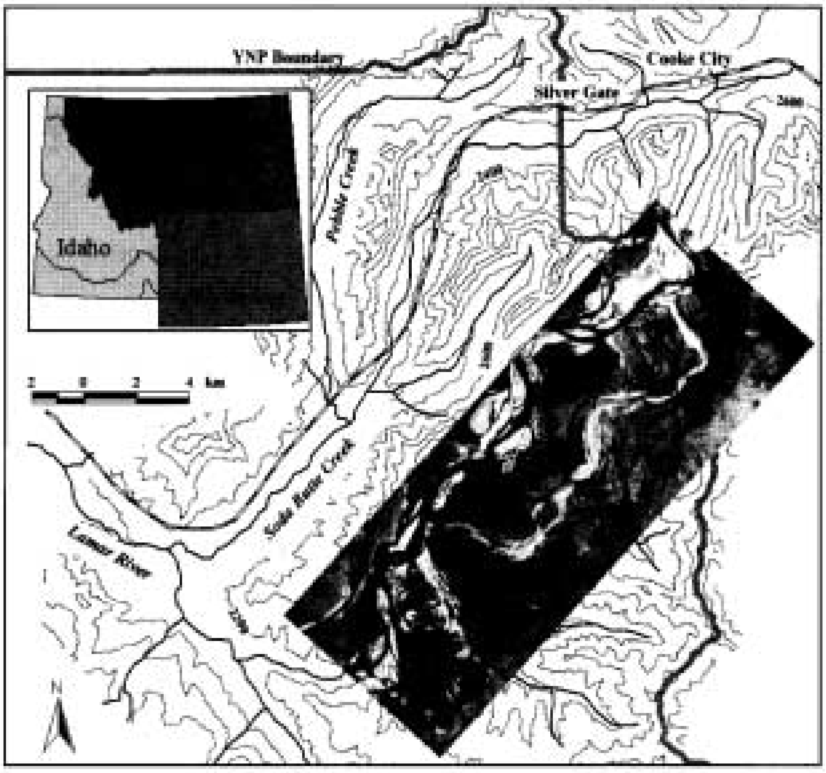

Figure 1. Map of the study area. The image of the Footbridge Reach of Soda Butte Creek is from the PROBE-1 1-m resolution data acquired on 03 August 1999.

The expanding availability of high resolution imagery (from both airborne and satellite-based sensors) and increasing affordability of hyperspectral imagery raises fundamental questions of what are the optimal spatial and spectral resolutions that are both *feasible* and *accurate* for remote mapping of in-stream habitats? We evaluated hyperspectral and simulated multispectral imagery to address the following specific objectives: (1) determine how effectively in-stream habitats could be remotely mapped; (2) explore alternative sensor specifications by examining the effects of spectral, spatial, and radiometric resolution on classification accuracy; and (3) develop guidelines for future applications of remote sensing of stream environments.

Methods

Study Area

Imagery was acquired and field data collected along a 2-km long, fourth-order segment of Soda Butte Creek in the northeast corner of Yellowstone National Park (Figure 1). Soda Butte Creek, typically 25 to 30 m wide, encompasses a diverse array of fluvial features and in-stream habitats (Figure 2). The stream consists of both single channel and braided sections displaying a mix of turbulence levels ranging from shallow, smooth flow through glides to patches of white water in high gradient riffles. The substrate ranges from predominantly sand in areas of reduced current velocity, such as eddy drop zones, to coarser cobble beds in higher energy riffle environments. Streamside vegetation consists of riparian meadow species devoid of trees or bushes that might obscure the sensor's view of the channel or cast shadows upon the stream. Depths in the study reach range from zero near shorelines to 1.2 m in certain pools.

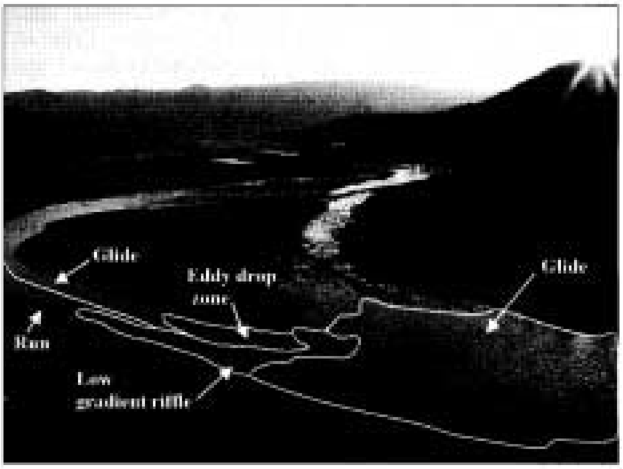

Figure 2. A portion of the Footbridge Reach of Soda Butte Creek, Yellowstone National Park. Note that units mapped by field surveyors are not homogeneous. Glides, for example, often exhibit areas of riffle-like surface texture, while eddy drop zones may have depths and surface roughness similar to glides.

Data Collection

The PROBE-1 sensor acquired digital image data for the study area on 03 August 1999. Water conditions were clear, and the field crew could easily see the streambed. Discharge at the USGS gage on Soda Butte Creek was 3.9 m^3/s (139 cfs) on the image acquisition date.

PROBE-1 is a cross-track scanner featuring 128 contiguous bands that cover the visible to shortwave-infrared portions of the spectrum from 0.438 to 2.507 μm with a spectral bandwidth of 16 to 20 nm; data are recorded with 11-bit radiometric resolution. For this study, the sensor was side-mounted on an A-Star Aerospatiale helicopter flying 600 m above the ground surface to provide an approximate spatial resolution of 1 m.

The hyperspectral data were downloaded immediately following the overflight, and true color composites were printed. Within ten days of image acquisition, in-stream habitats were mapped directly to these hard copies of the imagery to ensure precise co-registration of the field maps and image data. Surveyors identified and delineated seven in-stream habitat types, following a slightly modified (Ladd *et al.*, 1998) version of the Bisson *et al.* (1982) classification scheme widely used by federal and state resource management agencies (Table 1). We subsequently merged the original field data into a revised four-unit classification (Table 1) that more closely matched the way most field personnel map these habitats in practice, while maintaining clear distinctions among different hydrologic environments and increasing the sample size (i.e., the number of pixels) for the eddy drop zone and standing water units. These two habitat types were also merged for analysis of the simulated 2.5-m multispectral imagery and the 2-m buffered polygons in order to increase sample size, resulting in six rather than seven morphologic units for classification of those images.

Image Processing and Classification

The field maps enabled us to accurately digitize morphologic units on-screen using the imagery as a backdrop without the need for georectification. The image was not atmospherically corrected because most standard algorithms (e.g., ATREM) actually exacerbate error over water surfaces (Boardman, personal communication, 2001). To assess the effects of transitional areas between adjacent in-stream habitats on classification accuracy, 1- and 2-m interior buffers were applied to the morphologic unit polygons to eliminate uncertain boundary areas.

We manipulated the original hyperspectral data to create a series of new, resampled images that enabled us to compare directly different levels of spectral, spatial, and radiometric resolution. Although many high quality high-resolution multispectral instruments are currently available, we had to select one as a benchmark for comparison in this study. We chose an airborne, multispectral, eight-band sensor (ATLAS; Rickman and Luvall, 2001) with coarser spatial (2.5-m) and radiometric (8-bit) resolutions.

The original imagery was coarsened to 2.5-m pixels and both the original 1-m and resampled 2.5-m imagery were converted from 11-bit to 8-bit data by linear rescaling. We addressed the issue of spectral resolution by applying a filter function based upon the spectral sensitivity curves for the ATLAS multispectral sensor (Rickman and Luvall, unpublished data) to these four images to closely approximate the multispectral visible through shortwave infrared band coverage. This procedure resulted in a total of eight PROBE-1-derived data sets for all possible combinations of spectral (PROBE-1 hyperspectral or simulated ATLAS multispectral), spatial (1-m or 2.5-m pixels), and radiometric (11- or 8-bit data) resolution. Although these procedures did not produce imagery identical to data collected at these reduced resolutions, they enabled analyses that controlled for one variable at a time without confounding factors such as varying sensor signal-to-noise.

For each image, areas outside the active stream channel were masked out and a principal-components-transformed image was generated. For all of the hyperspectral images, the first 15 principal components were retained, capturing at least 95 percent of the variability within the 128 spectral bands. Classifications of the simulated multispectral imagery were conducted using the original eight bands rather than principal-components-transformed data because higher overall classification accuracies were obtained using the non-transformed data.

Supervised classification of both the PC-transformed and raw images followed standard maximum-likelihood procedures (Richards, 1994). Training site pixels were randomly selected from within field map polygons of each in-stream habitat type. The validation dataset consisted of all pixels within these polygons that were not chosen as training sites. Although the training pixels and ground reference data were both derived from the same field map polygons, none of the training sites were included in the validation data set used for accuracy assessment. Error matrices and Kappa statistics (Congalton and Green, 1999) were computed on a pixel-wise basis and used to evaluate classification accuracies.

Results

Overall accuracies and Kappa statistics generated with 1- and 2.5-m seven-unit classifications were approximately the same (Table 2). In the case of the four-unit classification, however, the 1-m data outperformed the 2.5-m data by 4.7 percent, indicating that finer spatial resolution can improve results. All comparisons of Kappa statistics were statistically significantly different (p-values less than 0.05), primarily as a result of large sample sizes.

TABLE 1. NAMES AND DESCRIPTIONS OF THE IN-STREAM HABITAT CLASSIFICATION SYSTEM UTILIZED IN THIS STUDY, MODIFIED FROM BISSON *ET AL.* (1982) AND LADD *ET AL.* (1998)

Seven-Unit Classification	
In-Stream Habitat Type	Morphologic Description
High gradient riffles (HGR)	characterized by fast-flowing white water over steep, relatively shallow areas
Low gradient riffles (LGR)	have gentler slopes, less surface turbulence, and no white water
Runs	consist of relatively deep water in a strong, focused current
Glides	similar to runs but featuring shallower, slower flow with less turbulence
Pools	the deepest in-stream habitat, displaying low surface turbulence, but often having coarse substrates and high flow velocities
Eddy drop zones (EDZ)	where fine grained sediments are deposited in areas of recirculating current
Standing water	occurs in abandoned channels separated from the primary route of flow
Four-Unit Classification	
Riffles	a single category consisting of both high gradient and low gradient riffles
Glides	includes both runs and glides
Pools	identical to the original seven-unit classification scheme
Eddy drop zone/standing water	a combination of the two original units

TABLE 2. ACCURACY RESULTS COMPARING EFFECTS OF SPATIAL, SPECTRAL, AND RADIOMETRIC RESOLUTION. ALL COMPARISONS OF KAPPA STATISTICS WERE STATISTICALLY SIGNIFICANTLY DIFFERENT (p-VALUES < 0.05), PRIMARILY AS A RESULT OF LARGE SAMPLE SIZES

Spatial Resolution				
	Seven Habitat Types		Four Habitat Types	
(Hyperspectral, 11-bit)	1 m	2.5 m	1 m	2.5 m
Overall Accuracy (%)	41.9	42.0	62.0	57.3
Kappa Value	0.23	0.23	0.29	0.29
Sample Size (pixels)	26,470	3,852	26,775	3,852
Radiometric Resolution				
	Seven Habitat Types		Four Habitat Types	
(Hyperspectral, 1-m)	11 bit	8 bit	11 bit	8 bit
Overall Accuracy (%)	41.9	39.8	62.0	61.2
Kappa Value	0.23	0.20	0.29	0.28
Sample Size (pixels)	26,470	26,470	26,775	26,775
Spectral Resolution				
	Seven Habitat Types		Four Habitat Types	
(1-m, 11-bit data)	Hyper-spectral	Multi-spectral	Hyper-spectral	Multi-spectral
Overall Accuracy (%)	41.9	34.7	62.0	58.6
Kappa Value	0.23	0.16	0.29	0.25
Sample Size (pixels)	26,470	26,470	26,775	26,775

The greatest advantage provided by increased spatial resolution resulted from the buffering capability permitted by the smaller pixel size. The 1-m image had 6.25 times more pixels than the 2.5-m image within the active stream channel, which allowed us to spatially buffer the 1-m scale habitat units in order to remove the outer pixels of each polygon. The buffering improved overall classification accuracies (Table 3) because it removed many mixed pixels, deleted some transitional areas with mixed spectral characteristics (Figure 2), and focused on the central core of units rather than the boundary lines, which might have been mapped incorrectly in the field. The 2.5-m imagery, on the other hand, could not be spatially buffered because the buffers completely deleted many of the units.

Higher radiometric resolution slightly improved overall accuracy (Table 2). Accuracies increased by 0.8 percent for the four-unit and 2.1 percent for the seven-unit classifications.

TABLE 3. CLASSIFICATION ACCURACIES SHOWING THE IMPROVEMENT PRODUCED BY SPATIAL BUFFERING OF HABITAT UNITS USING THE 1-m PROBE-1 HYPERSPECTRAL IMAGERY. THE CLASSIFICATIONS USING THE 2-m BUFFER WERE FOR SIX UNITS (EDDY DROP ZONES AND STANDING WATER WERE MERGED INTO A SINGLE CLASS) RATHER THAN THE ORIGINAL SEVEN. THE 2.5-m IMAGERY COULD NOT BE BUFFERED BECAUSE IT LED TO COMPLETE REMOVAL OF MANY UNITS

	Polygon Buffer Size		
	Unbuffered	1-m buffer	2-m buffer
Overall Accuracy (%)			
7(6) units	41.9	50.3	57.5
4 units	62.0	69.1	72.3
Kappa Value			
7(6) units	0.23	0.30	0.36
4 units	0.29	0.30	0.31
Sample Size (pixels)			
7(6) units	26,470	16,594	9,887
4 units	26,775	17,202	10,166

Spectrally resampling the PROBE-1 data with a filter function designed to closely mimic a multispectral sensor's bands allowed a direct comparison of hyperspectral and multispectral data by isolating the effect of spectral resolution on classification accuracy, independent of instrument characteristics (e.g., signal-to-noise ratio, radiometric resolution, etc.). The hyperspectral resolution and nearly continuous spectral coverage improved overall accuracies relative to the simulated multispectral data by 7.2 percent and 3.4 percent for seven-unit and four-unit classifications, respectively (Table 2).

Discussion

Sensor and Resolution Selection for Stream Mapping

Our analysis focused on isolating the effects of spatial, radiometric, and spectral resolution. Enhanced spectral resolution improved remote mapping of in-stream habitats to a greater extent than did increased spatial or radiometric resolution (Table 2). The often subtle variations among some units required more detailed spectral information in order to effectively capture differences among similar habitat types. The improvement provided by hyperspectral imagery was greatest (7.2 percent) for the seven-unit classification, where detecting relatively minor distinctions between similar units (e.g., glides and runs, or high gradient and low gradient riffles) was crucial to accurate identification of in-stream habitats (Table 2). In contrast, the hyperspectral imagery is only 3.4 percent more accurate than multispectral imagery when the in-stream habitats are broken into only four, more spectrally separable classes.

However, instrument electromechanical characteristics, including signal-to-noise ratio and gain settings, will also influence classification accuracies. In resampling PROBE-1 data to simulate a multispectral sensor, we were unable to take these effects into account, and the analysis of simulated imagery presented here was not necessarily equivalent to collecting data at a coarser spatial, spectral, and/or radiometric resolution. There are likely to be substantial differences in accuracy between classifications derived from actual and simulated multispectral data.

An actual ATLAS 2.5-m resolution image collected over the study area on 25 August 1999, 22 days after the PROBE-1 imagery was collected, provides a possible illustration of the importance of these instrument characteristics. Although no substantial changes in in-stream habitats were noted in the field during this period of baseflow, the discharge had dropped to 2.1 m^3/s (74 cfs) and the reduction in depth might have affected the water's spectral characteristics. Additional factors ranging from differences in sun angle to variations in turbidity and algal growth also precluded definitive conclusions about instrument performance based on direct comparisons of classifications derived from the simulated and actual ATLAS data sets. However, the difference in classification accuracies between actual and simulated ATLAS imagery was sufficiently large (Table 4) to suggest that sensor characteristics might play as large a role in determining how effectively in-stream habitats can be remotely mapped as do spectral, spatial, or radiometric resolution. Regardless of whether one examines the simulated

TABLE 4. DIFFERENCES IN SENSOR CHARACTERISTICS AS INDICATED BY CLASSIFICATION ACCURACIES FOR ACTUAL AND SIMULATED 8-BIT, 2.5-m ATLAS IMAGERY

	Seven Habitat Types		Four Habitat Types	
	Simulated ATLAS	ATLAS	Simulated ATLAS	ATLAS
Overall Accuracy (%)	34.7	22.6	54.5	28.5
Kappa Value	0.16	0.06	0.20	0.06

or actual ATLAS data, our results suggested that modern hyperspectral sensors, which often combine higher spectral resolution, higher radiometric resolution, and enhanced instrument precision relative to multispectral sensors, might provide the best tool for stream mapping.

The physical dimensions of the river and features of interest in large part determine the level of spatial resolution needed for a given application, and in our study a higher ratio of stream width to pixel size (~25:1 for 1-m data vs. ~ 10:1 for the 2.5-m data) provided the most accurate classification of in-stream habitats. For larger rivers featuring more sizable in-stream habitat units, imagery of a coarser spatial resolution, with reduced cost and data volume, would still maintain the same ratio of stream width to pixel size and therefore might provide similar accuracies. Alternatively, using high-resolution data in larger rivers might allow stream surveys to achieve the accuracies typically expected of remote sensing classifications (Marcus, 2002). In addition, an inherent advantage of smaller pixel sizes is the ability to study narrower, low-order streams and reduce the number of mixed pixels, an important consideration in morphologically complex channels. Imagery of sufficient resolution can also detect and illustrate spatial heterogeneity within the channel, identifying key habitat areas on a pixel-by-pixel basis to provide a more thorough inventory of stream condition.

In this study, even though the fine scale 1-m resolution did not dramatically enhance classification accuracies, it enabled spatial buffering that did significantly improve accuracies (Table 3). However, the difficulties in mounting instruments on a helicopter are substantial, and hyperspectral data at this level of spatial resolution might not currently be worth the effort (and 6.25 times increase in data volume) for stream mapping. The significantly better results from buffered images suggest that acquiring imagery of sufficiently high resolution to provide a ratio of pixel size to stream width on the order of 25:1 will be appropriate for studies in small streams if future improvements in technology make it more feasible. At present, larger, fifth- and sixth-order rivers might be effectively mapped using coarser spatial resolution imagery, which could be acquired less expensively from more stable, higher-altitude platforms. Remote sensing of smaller mountain streams like Soda Butte Creek represents a greater challenge, but our results illustrated the potential of this approach.

The minor effects of radiometric resolution on stream classification accuracy were unexpected (Table 2). We had suspected that a sensor capable of measuring smaller variations in reflected energy would better distinguish among subtly different stream features due to the low reflectance of water, especially in the infrared bands. The 11-bit imagery did perform 0.8 percent (four units) to 2.1 percent (seven units) better in classification accuracy than the 8-bit imagery, but this might not be a large enough improvement to justify acquiring an 11-bit sensor for the sole purpose of increasing radiometric detail, with the drawback of increased data volume.

Additional Limiting Factors

The field maps used to train and validate the image classifications, rather than any fundamental shortcomings of the remotely sensed data, might well have been the largest factor limiting classification accuracy (Marcus, 2002). Transformed divergence statistics (Jensen, 1996) for this study's hyperspectral data indicated that all pair-wise comparisons of in-stream habitats were spectrally distinct, with the sole exception of standing water compared to eddy drop zones. These spectral differences between unit types suggested that classification accuracies should be higher than the 37 percent to 62 percent we obtained using hyperspectral imagery. Existing field-based stream classification methods attempt to divide the continuum of fluvial forms and processes into discrete morphological entities using arbitrarily defined and subjectively applied criteria (Goodwin, 1999). The dramatic improvements produced by buffering the habitat units (Table 3) indicated that field mapping of transitional areas into the wrong habitat types generated a good portion of the "misclassification." Supervised image classifications are only as valid as the training sites from which they are developed (Congalton, 1991); the low overall accuracies in this study might be a consequence of the inadequacy of the original field maps.

We believe remotely sensed hyperspectral imagery might map stream morphology *more* effectively than field crews. Spectrally driven classifications map pixels on an individual basis, independent of the surrounding pixels, to provide a detailed pixel-by-pixel portrayal of stream morphology. Field teams lumping spatially variable habitat types into large homogeneous areas miss this fine scale spatial heterogeneity.

By way of examples, Plate 1 contrasts the polygon-based field map with the pixel-by-pixel PROBE-1 image classification of habitat units. In the classified image, a gradation between the glide and low-gradient riffle and from the riffle into the run downstream was clearly visible and entirely reasonable, yet absent in the field map. Even more remarkable was the image classification of bankside pixels as standing water, which was accurate for these very shallow, zero velocity portions of the stream, although our field team lumped these shoreline features into the larger in-stream habitat type (Figure 2 and Plate 1). The eddy drop zone locations derived from the image classification were also mostly in slack water locations that were hydraulically reasonable, but were too small (often only one pixel in size) to be mapped in the field. The question then arises as to whether our field maps adequately depicted the complex nature of fluvial systems, and it logically follows that classification accuracy was limited by our oversimplified representation of stream morphology. Close examination of the entire classified image yielded similar results, fostering the somewhat disturbing but promising notion that the remotely sensed data might have been the most accurate map, and that our error matrices were actually an evaluation of the accuracy of our field mapping rather than an evaluation of the image classes. Determining classification "accuracy" becomes a major methodological hurdle when the imagery might be more accurate than the field maps.

In light of the unacceptably low classification accuracies obtained in this study, an alternative solution would be to employ an unsupervised approach. Defining distinct image classes based upon the stream's inherent spectral variability would eliminate dependence upon a field-based habitat classification scheme and thus avoid the subjectivity introduced by supervised image classification. Allowing stream ecologists and resource managers to interpret spectrally clustered image classes in terms of in-stream habitats might provide a more useful tool.

In addition to the constraints placed on accuracy by field mapping techniques, the classification methods employed were probably limiting. For both the multispectral and hyperspectral imagery, we used a single approach appropriate for both types of imagery, supervised maximum-likelihood classification. Using a single technique enabled us to compare directly the quality of the imagery, including varying resolutions. More sophisticated classification methods are available, however, especially for the hyperspectral imagery, such as spectral feature fitting, discriminant analysis, or classification and regression trees. Use of alternate, more advanced classification algorithms for the hyperspectral imagery would likely have resulted in higher accuracies.

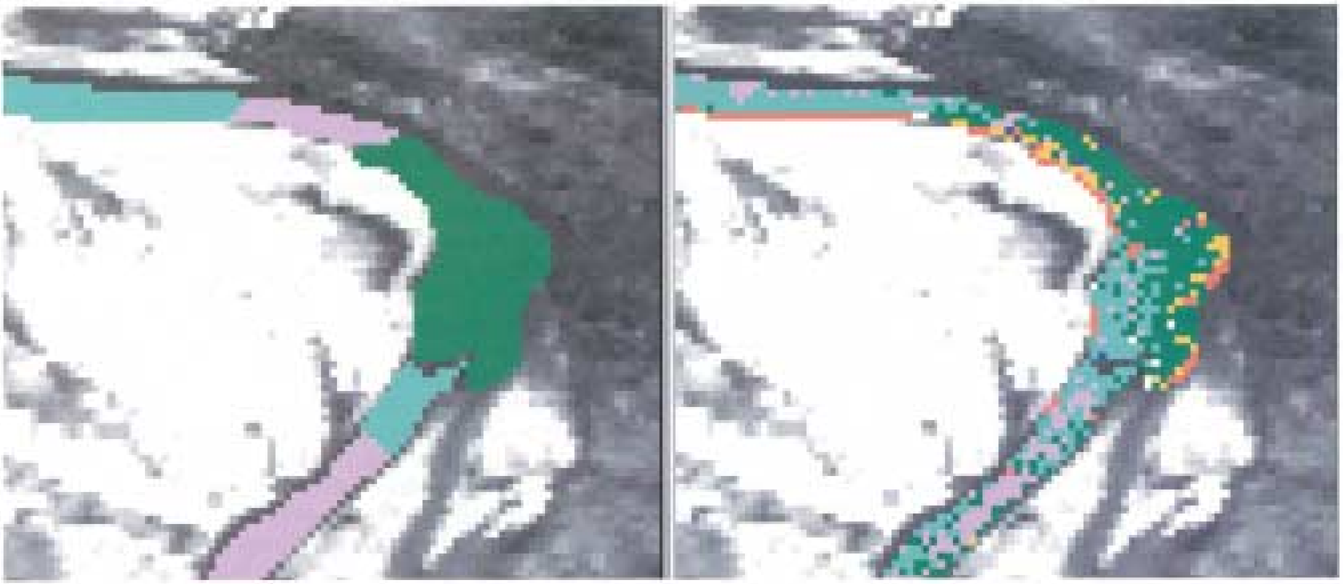

Plate 1. Field map polygons used for ground reference data (left) and morphologic unit classification derived from the 1-m hyperspectral data. The classified image displays the spatial heterogeneity that occurred in transition zones between units and along shorelines.

Conclusion

The results of this study attest to the potential of remote sensing technology as a tool for mapping in-stream habitats. This approach permits the extensive, frequent coverage required to effectively monitor stream condition and change over entire watersheds. We have addressed the effects of sensor resolution on remote mapping of stream morphology on a fourth-order mountain river, but our findings apply to streams of other types and scales as well. Enhanced spectral resolution improves image classifications by capturing subtle distinctions among the reflectance properties of similar habitat types, indicating that hyperspectral rather than multispectral sensors will provide more accurate classifications. Instrument electromechanical characteristics (e.g., signal-to-noise ratio) also influence results. Optimal spatial resolution depends upon the physical dimensions of the river under study, with the ratio of pixel size to the size of typical in-stream habitats affecting classification accuracy. Relatively coarser spatial resolution imagery might be effective for mapping higher-order rivers with large, homogeneous in-stream habitats, but smaller streams featuring spatially variable, meter-scale habitat units require finer resolution.

The character of the channel and its surroundings are also important considerations. Higher spatial resolution might be more important for morphologically complex braided streams than for relatively simple single-channel straight or meandering rivers. Mountain streams in forested canyons cannot be effectively examined in this manner because remote mapping of in-stream habitats is limited to environments devoid of overhanging vegetation or extensive shadows. In appropriate settings, however, the ability to obtain a detailed pixel-by-pixel portrayal of the spatial distribution of in-stream habitats suggests that remote mapping might become a valuable tool for resource managers wishing to quantify habitat availability and monitor system response to various disturbance regimes.

The results of this study were at first discouraging because, on the basis of accuracy statistics alone (Tables 2 and 3), the potential for widespread mapping of streams with high spatial resolution digital imagery appeared rather limited. We believe, however, that the imagery was capable of providing maps that were more accurate in many places than the ground-based field surveys. The reader is presented with this conundrum: Which to believe, the error matrix statistics or the visual impression given by the classification results (Plate 1)?

The future's primary challenge will be in revising traditional methods of ground reference data collection and classical conceptions of in-stream habitats in order to more effectively assess the accuracy of image-based classifications. Ground reference data collection campaigns must be planned around what the sensor sees, and the sensor does not group habitats into large, homogeneous areas divided by hard line boundaries. Indeed, the polygon field maps we used to obtain validation data in this study proved inadequate. A superior alternative might be to randomly select points at which to compare the image classification to a field-based designation of the in-stream habitat at that specific location rather than for some larger area of the channel. This point-based approach is more representative of reality, because distinct, channel-spanning polygons fail to capture the fine scale spatial heterogeneity of habitat types available in any given stream reach. This also has implications for training site selection, which might similarly proceed by sampling isolated points in the channel, categorizing in the field the in-stream habitat at these points, and then using this information to drive subsequent image classifications.

Alternatively, an unsupervised approach might be employed and spectrally defined image classes interpreted in terms of in-stream habitats. In any case, we suggest a departure from traditional polygon-based ideas of in-stream habitat that subdivide the river's continuum of habitat types into discrete entities, and we recommend as an alternative a cellular conceptualization of the fluvial environment. Future studies designed in accordance with this ontological framework will advance the potential of remote sensing of rivers.

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