challenges

Commentary

Challenges in Aquatic Physical Habitat Assessment: Improving Conservation and Restoration Decisions for Contemporary Watersheds

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Received: 7 October 2017; Accepted: 4 December 2017; Published: 5 December 2017

Abstract: Attribution of in-stream biological impairment to anthropogenic activities and prioritization for restoration and/or conservation can be challenging in contemporary mixed-land-use watersheds. Critical information necessary to improve decision making can be costly and labor intensive, and thus unobtainable for many municipalities. A reduced cost, *rapid* stream physical habitat assessment (rPHA) can yield information that, when paired with land use data may reveal causal patterns in aquatic physical habitat degradation, and thus assist targeting sites for restoration. However, a great deal of work is needed to reduce associated costs, and validate the potential of rPHA for documenting fine-scale incremental change in physical habitat conditions in complex contemporary watersheds. The following commentary serves to draw attention to rPHA challenges and research needs including (but not limited to) field-based validation and optimization of new remote sensing technologies, evaluation of the accuracy and representativeness of rapid vegetation survey methods, refinement of analytical methods, and consideration of legacy land use impacts and hydrologic system evolution in rPHA results interpretation. Considering the value of rPHA-generated data for improvement of watershed resource management, such challenges constitute timely, high-impact research opportunities for investigators wishing to advance complex, contemporary aquatic ecosystem management.

Keywords: drone-based remote sensing; aquatic ecosystems; rapid physical habitat assessment; hydrogeomorphology; mixed-land-use watersheds; urban watersheds; biological impairment; stream restoration; legacy effects; aquatic vegetation

1. Introduction

1.1. Background

Stream physical habitat is formed through the interaction of geomorphic and hydrologic processes, which are spatially and temporally dynamic [1,2]. Climate, geology, and topography largely determine watershed physiography, which, in turn, determines stream characteristics such as the composition of stream bed and bank material, and erodibility of hillslopes and stream channels [3]. Geomorphic habitat features such as pool and riffle sequence, and channel slope and shape are also influenced by hydrologic processes, which are similarly determined by climate and watershed physiography [4,5]. Streamflow and stream geomorphology integrate to form aquatic physical habitat that varies longitudinally from headwaters to mouth [1,2]. Therefore, quantifying stream physical habitat provides insight regarding basin-specific characteristics (e.g., hydrology, climate, physiography) and perturbations potentially impacting aquatic communities in a given stream ecosystem [5].

Human activities alter the landscape and disrupt natural hydrologic, geologic, and morphologic processes that influence the formation of stream physical habitat [1,6]. Often, initial impacts of human landscape development include removal of vegetative cover [7], the consequences of which are varied. However, as the terrestrial landscape is cleared of vegetated cover, increased overland flow commonly leads to accelerated erosion of upland soils, increased streamflow volume, advanced peak hydrograph, and deposition of upland and in-stream (i.e., due to bank erosion, streambed scouring) soil within the stream [6]. Stream sedimentation interferes with natural hydrogeomorphological processes, because it fills channel and interstitial pore spaces and can displace flow through the formation of in-stream bars [7]. The decrease in channel carrying capacity of streamflow increases flooding, and encourages sediment deposition within the area adjacent to the stream (i.e., the floodplain) [8]. Increases in sediment load and streamflow volume and velocity that persist over time can result in erosion (banks) and incision (bed), and thus widening and deepening of the channel [9]. As a consequence, physical habitat becomes morphologically simpler, and the complexity within aquatic communities and overall stream ecosystem function can deteriorate [1,10].

Agricultural land use practices are a leading influence of hydrogeomorphological alterations, and are understood to typically result in increased streamflow, decreased water quality, and degraded physical habitat [7]. For example, as much as ten times the concentration of sediment has been documented in streams draining agricultural lands relative to undisturbed watersheds [6]. Livestock grazing, which often contributes to reduced vegetative cover, can also compact the soil surface, thereby decreasing the rate of precipitation infiltration, increasing overland flow (i.e., stormwater), and thus simultaneously contributing to higher streamflows and greater stream sediment loads [9]. The addition of drainage features on cultivated land also augments streamflow; surface runoff is transported more efficiently across the landscape in drainage ditches, and wetland area is reduced through the use of subsurface (tile) drains [3]. The combined effect of increased sediment supply and enhanced stormwater delivery to streams in agricultural landscapes results in altered channel morphology as the sediment and flow inputs increase streambank erosion and destabilize the channel [4]. Because the land is rarely converted back to forest or vegetative cover, altered hydrogeomorphology often persists over time, thus perpetuating physical habitat degradation [3]. Urban land uses influence the hydrogeomorphology of a stream system, mainly through increased overland flow [8] via construction of parking areas, roads, sidewalks, roofs (i.e., impervious surfaces), and artificial drainage structures that deliver precipitation to nearby streams more quickly and efficiently [11]. Reference [9] investigated the impacts of urbanization on flow timing and volume in streams of the southeastern United States. Study outcomes indicated annual flood peak magnification of 8–33% in agricultural watersheds and 22–84% in urbanized catchments, relative to areas of minimal disturbance [9]. The higher percentage of peak flows in urban streams suggests that engineered drainage systems typically installed in urban centers can have a disproportionate effect on stream hydrology [8].

While urbanization, agriculture, and other related modes of development are leading stressors of stream hydrogeomorphology, other common land use practices, such as natural resource extraction, have also been shown to alter geomorphology and watershed hydrology [12]. For example, surface coal mining has been a historic driver of landscape alteration in many regions, as it is frequently accompanied by removal of both vegetation and soil while changing catchment structure through practices such as valley filling [13]. Valley fills change the original channel geometry of headwater streams, as spoil material is deposited in the stream channel [14], altering hydrology, hydrogeomorphology, and aquatic physical habitat. Ultimately, regardless of the type of land use practice, there are often multiple impacts to aquatic hydro-ecological status. Determining where those impacts are greatest, in order to guide mitigation investments, can be a costly challenge.

1.2. Assessing Aquatic Physical Habitat

Aquatic physical habitat can be evaluated by examining biological, chemical, hydrological, or physical response to human influences [2]. Biological evaluation of a stream may focus on aquatic plant or animal response to human activity, while chemical evaluation focuses on measuring constituents within the water such as nutrients, pesticides, and other dissolved and/or suspended components [8]. Hydrologic evaluation of stream condition comprises quantitative characterization of the change in frequency, magnitude, duration, and timing of water delivered to a stream system [15]. The concept of stream physical habitat encompasses all of the required biological, chemical, and physical attributes needed to sustain the organisms that live in a stream [2]. Since stream geomorphic condition is strongly tied to aquatic habitat and aquatic community composition, and consequently aquatic ecological food webs and water quality, hydro-ecological geomorphic assessment (i.e., aquatic physical habitat assessment (PHA)) is an ideal method for evaluating stream biological condition [16].

In watersheds with a combination of agriculture, urbanization, industry, and mining (i.e., mixed-land-use watersheds) it can be challenging to link specific land use activities to degraded biological condition or biological impairment [3,17–19]. Biological impairment can be the result of land use practices, hydrology, water quality alteration, or other aquatic habitat limitations, and is most often a combination of factors [1]. For example, indices-based biological assessment methods (such as Index of Biological Integrity, or IBI) assume that the condition of the surrounding physical habitat will be reflected in the biological composition of a stream, but the method seldom provides information about which physical factors (i.e., causal mechanisms) are specifically responsible for a given stream's biological state [2].

Channel degradation and aquatic community impairment are among the most common reasons for initiating stream restoration and enhancement projects, and large fiscal and labor investments are often dedicated to treat observed/observable symptoms prior to fully exploring the causes [20]. A physical habitat assessment (PHA) includes observations and measurements of stream habitat features at predetermined intervals along the length of a given stream or river. Depending upon the scale of the study, a PHA can provide detailed information about the condition of the streambed and streambanks, and the availability of habitats for macroinvertebrates and other aquatic biota [21,22]. For example, longitudinal analysis of changes in substrate can identify potential areas of sediment deposition, or homogenization of streambed habitat due to vertical embedding (i.e., depth of fine substrate surrounding larger particles) [23]. Other useful information may include identification of specific types of degradation (e.g., mass wasting of streambanks, trash deposits, etc.) and potential sites for stream restoration [23].

A stream PHA can yield information that, when paired with land use data may reveal causal patterns in aquatic physical habitat degradation and help to identify sites for rehabilitation or restoration. Reference [1] developed a rapid PHA (rPHA) for contemporary mixed-land-use (including municipal) watersheds. The rapid PHA method was developed to (a) reduce the time and cost often required for such assessments, thus making it a feasible method for fiscally-constrained municipalities, and (b) establish a method that can be easily adapted for mixed-land-use watersheds in any location (globally) to achieve desired outcomes through focused applications for specific variables [1]. For example, a high spatial resolution study of physical habitat along a given reach, or a study with less-frequent assessment intervals of an entire stream can provide quantitative (and defensible) information about longitudinal variation of specific habitat features and hydrologic responses to watershed-scale land use activities [24]. Recent technologies have advanced the use of geographic information systems (GIS) and computer-based models for geomorphic investigations [25]. However, GIS and/or geomorphic data generated using models may not be directly representative of the hydro-ecological condition of a stream [16], indicating a need for collection of observed data to be used in combination with models. The ability to directly compare observed data with GIS data and model-generated information could provide a valuable opportunity to understand how data produced by the different methods may contrast. However, a great deal of work is necessary to validate the rPHA as a defensible tool to document aquatic physical habitat and biological conditions in contemporary mixed-land-use watersheds. Such advances, if successful, could more accurately inform restoration activities, establish a baseline of aquatic physical habitat condition for future studies, facilitate municipal investments in aquatic ecosystem restoration, and greatly reduce costs associated with mitigation of impaired waters and waterways [1].

2. Objectives

The purpose of this invited commentary is to draw attention to challenges and, thus, needed research in rPHA development. It is neither the intent, nor the scope, to address all challenge areas. However, given the potential of the method to advance land management through focused investigation and subsequent physical, mechanistic mitigation practices, and to substantially reduce costs in so-doing, improvements (addressed herein) to the methods and integrated technologies will further increase efficiencies and aid in utilizing federal, state, and other tax-payer dollars most effectively. These benefits provide the basis for great interest in advancing the method. Challenges, and thus needed advancements, exist in many areas; four fundamental areas are addressed here including, (1) Geographic Information Systems (GIS) and Remote Sensing (RS) applications, (2) vegetation (terrestrial and aquatic) survey methods, (3) analytical methods, and (4) legacy effects of historic practices. While additional challenges may exist depending on physiographic location, types and intensities of development, municipal and aquatic health needs, etc., the challenges identified in this article create the basis for needed activities that will advance the applicability of the method globally.

3. Discussion

3.1. The rPHA Method (in Brief), Challenges and Research Needs

Variability of stream or river physical conditions can indicate how resilient a given system may be to stresses, and/or how it may respond to restoration activities [26,27]. For example, variation in characteristics such as channel morphology, riparian vegetation, and streambed sediment can indicate status as well as specific management or restoration practices that will be most effective [28]. Variables can also be measured that provide information about the condition of the streambed and streambanks and sources of microhabitats for macroinvertebrates and other aquatic biota [21,22]. For example, quantification of substrate types can be used to identify potential areas of sediment deposition, or homogenization of habitat due to vertical embedding of gravel (depth of fine substrate such as sand, silt or clay vertically around larger particles) [23]. Channel incision, and channel widening or narrowing can be indicators of aquatic system hydrologic stressors, including deforestation, agricultural activities, and/or increased urbanization [3,15]. To be most informative, an rPHA can be conducted at any spatial or temporal frequency. Temporal and spatial frequency can be determined by establishing the amount of time, labor, and financial support available to collect the desired information. The method is therefore flexible, such that information can be collected along the entire length of a stream, or at select points along the stream identified using GIS and/or other RS technologies. The assessment can be conducted by one or more individuals with only minor adjustments. Data collection criteria and the order of field operations may also vary by site, application, and desired outcomes. For additional details the reader is referenced to [1] and citations therein.

3.1.1. Challenges Using Geographic Information Systems and Remote Sensing

Geographic Information Systems (GIS) and Remote Sensing (RS) technologies have been utilized for natural resource evaluation, monitoring, and management for many decades, particularly at large scales and in interdisciplinary applications such as watershed planning and management [29–31]. While advancements in both GIS analyses and RS technologies now routinely allow for a much finer scale of inquiry, challenges persist in determining accuracy and cost thresholds of these new tools and methods to support rPHA development. Drone-based RS technologies offer potential for delivering data with spatial, spectral, and temporal resolutions commensurate with rPHA requirements (i.e., sub-stream reach scale) at potentially significant cost savings over traditional field methods and manned-aircraft surveys. However, research is needed to validate optimal sensor or sensor combinations, workflow schemas, and software solutions to produce drone-based remote measurements comparable to field observations. Moreover, analyses that compare equipment and labor costs of drone-based GIS/RS approaches to traditional rPHA methods are needed.

Contemporary GIS/RS approaches are being developed to scale down from the watershed or basin level to the stream reach, including in some cases, characterization of channel morphology and other physical habitat attributes [32,33]. For example, Reference [33] demonstrated the integration of airborne Light Detecting and Ranging (LiDAR) technology and hyperspectral imagery to produce high spatial resolution geospatial data of topography, channel dimensions/complexity (e.g., width, depth, slope, riffles/pool spacing), hydraulic roughness, riparian integrity, and anthropogenic alterations. Similarly, Reference [32] revealed that helicopter-based RS and Structure-from-Motion (SfM) photogrammetry hold great promise for detailed riverscape mapping, including many parameters necessary for rPHA. However, airborne RS systems are often highly expensive, requiring manned-aircraft platforms. Moreover, should increased temporal resolution be desirable or necessary for sufficient rPHA results (e.g., such as in rapidly changing mixed-land-use watersheds), costly manned-aircraft ferry and mission time must be budgeted. Thus, investigations are needed that validate the use of small unmanned aerial systems (i.e., drones) and drone-equipped remote sensing technologies that reduce substantial costs of current airborne systems. Development of drones and parallel developments in sensor miniaturization offer many potential solutions [34]. Small, relatively inexpensive, and commercially available drones integrate sophisticated control systems (Global Navigation Satellite System [GNSS], Inertial Measurement Unit [IMU], Autopilot) with highly stable gimbal technology that can accommodate miniature sensors for RS including Red-Green-Blue (RGB) digital cameras, thermal cameras, multi-spectral cameras, LiDAR, and hyperspectral sensors [35]. Drones are most commonly multi-rotor or fixed-wing, both of which can be configured to fly autonomously, following pre-defined flight lines with overlap and at consistent altitudes for comprehensive mapping coverage. Fixed-wing models offer the advantage of longer persistence for larger area mapping. However, commercially available multi-rotor drones, with flight times of up to 30 min, are more maneuverable in and around riparian canopy and other such complex surfaces, and allow for vertical take-off and landing. Identifying optimal drone technologies for specific purposes provides yet another area of greatly needed investigation.

Recent successes in manned-aircraft RS of riverine environments demonstrates spatial and spectral resolutions that may meet accuracy requirements for measuring many rPHA variables, thus suggesting that similar results can be achieved with drone-based RS [33]. While drone-based spatial and spectral technologies can supply many rPHA quantitative data, determining the most appropriate drone-based sensor(s) to enhance the development of rPHA requires further research. Combining LiDAR and hyperspectral imaging capability on a drone platform may provide the most robust solution for remote sensing of rPHA metrics including land use, special features, canopy cover, bank and channel measurements, and riparian assessments [1]. However, while these sensors are currently being miniaturized for drone deployment, they are still prohibitively expensive in comparison to RGB digital cameras and require larger, heavier lift vehicles, thus representing another area of needed research and development.

A nearer term and more cost effective drone-based solution for rPHA might be exploiting SfM photogrammetry, which utilizes inexpensive consumer grade RGB digital cameras. Notably, near-infrared camera technology is equally inexpensive and can be easily added to a drone payload to expand spectral resolution and allow for vegetative health and soil moisture to be remotely sensed through indices such as the Normalized Difference Vegetation Index (NDVI). Reference [32] explained that SfM has become an inexpensive means of generating high spatial resolution (e.g., centimeter accuracy) orthophotographs and Digital Elevation Models (DEM) from multiple camera views that yield dense point-cloud data similar to single return LiDAR. As with LiDAR, SfM-derived topography and point clouds hold promise for supporting rPHA metrics above the water surface, but the technology requires a great deal of validation. In so-doing the technology may also offer solutions for bathymetric measurements such as thalweg depth or rootmat extent [34].

Ultimately, drone-based RS analyses have the potential to increase spatial, spectral, and temporal resolutions in support of rPHA and other stream, wetland, and watershed assessments. Nevertheless, experiments are needed to determine optimal vehicles (e.g., fixed-wing, multi-rotor), sensor packages (e.g., LiDAR, RGB, Hyperspectral), mission parameters (e.g., flight altitudes, flightline overlap, control targeting, weather), and data products (e.g., DEMs, triangulated irregular networks, topographic contours) that rival, if not exceed, results derived from field-based techniques. GNSS currently serves a critical role in drone mission ground control and flight operations, but could also be deployed in accuracy assessments comparing drone-based RS measurement to rPHA field observations. Finally, GNSS may also prove to be a valuable companion technology to augment drone-based RS for rPHA, particularly for underwater metrics and stream sections under heavy canopy.

3.1.2. Challenges in Vegetation Survey Methods

Vegetation surveys are time-consuming and labor intensive, yet riparian, bank, and in-stream vegetation is understood to be critically important for stream aquatic ecosystem function and for providing physical habitat [1]. Despite the availability of a number of methods for vegetation surveys, research is greatly needed to validate standard revised approaches for rPHA. Here, current procedures are presented (in brief), and needed advancements are identified. For example, an approach for estimating canopy cover (important for stream shading, water temperature, etc.) measurements includes use of a convex densiometer as per [1,23]. To prevent overlap of adjacent canopy measurements, the densiometer was modified after [36] in the work of [1]. During winter months, the number of line intersections covered by branches or remaining leaves was substituted for canopy cover. Reference [1] estimated canopy cover as the percentage of points on the densiometer covered by canopy as per [23]. Other traditional vegetation survey methods include plot and line intercept methods that yield information on a range of attributes (e.g., species frequency, cover, density) [37]. Data may be collected at the level of individual species (requiring most time and expertise) or at the level of functional types (e.g., based on growth habit: herbaceous (forb, grass), woody (shrub, tree), cover types (bare soil, woody debris, vegetation); ecological roles: native vs. non-native, or planted annual crops vs. perennial "natural" vegetation; or a combination thereof). Work is needed to validate modified methods with other more or less rigorous methods to approach a balance of data accuracy and available funds. Vegetation survey methods should also utilize emergent RS/photogrammetric methods for calculating stem and leaf densities with airborne LiDAR, but studies are needed to validate and advance such approaches.

There are needs for revised methods of vegetation surveys that consider streambanks, streamside riparian zones, shading and bank stability. For example, a rapid method for bank and riparian vegetation assessment, adapted from [38], includes transects established perpendicular to the grade (slope) spanning the entire riparian area. Transects are paced and the number of steps within each encountered cover type is recorded. Percent cover is calculated by dividing the number of steps within each category by the total number of steps. An even more rapid method, employed for fish habitat inventories [39] simply assesses whether the dominant vegetation cover type in a surveyed stream reach is wooded (trees) or meadow (herbaceous plants and shrubs). The former cover type has the potential to supply large quantities of woody debris (habitat) to the stream channel, while the latter does not. These methods are in need of validation in mixed-land-use drainages, and adaptation for banks and riparian areas to advance relevant information about the potential for shade, bank stability, and/or habitat (i.e., root wads).

Within the stream, plants (vascular plants, moss) and algae provide habitat and food, or represent a potential nuisance (in case of algal blooms) to invertebrates and fish. Plant/algal cover may be assessed in a similar way as terrestrial vegetation via line intercept sampling during baseflow conditions in wadeable streams (i.e., when the streambed is visible). At a sampling point, a transect perpendicular to the direction of flow is established by anchoring a measuring tape at each bank. At predefined intervals (providing ≥15 data points), the cover type directly below the tape is recorded. "Covered" is defined by what is directly below the tape and obscuring the stream bottom. Percent cover is calculated as the number of observations per cover class divided by the total number of observations. A similar method, using a 1 m wide belt transect was developed by [40] to assess algal blooms in streams. In terms of applications for the rPHA, recorded cover type (e.g., vascular plants, moss, macroscopic algae, or biofilm) and substrate (inorganic or woody; by size class, if desired) and recording frequency, may be customized to address the specific goals of the rPHA, but validation studies are critical to justify application methods. Thus, while many vegetation survey methods exists, few are designed specifically for rPHA in which it is critical to strike a balance between rigor and cost, and to verify thresholds of statistical significance necessary for confidence in decision making.

3.1.3. Analytical Challenges

Data analysis, including statistical methods, should remain a prominent tool for geomorphological (including rPHA) data assessment. However, identifying a balance between statistical rigor and hydro-ecological impact needs to be investigated in mixed-land-use watersheds, particularly since statistically insignificant geomorphological changes can have ecologically significant impacts. Therefore, a great deal of work is needed to advance analytical techniques that add confidence in data but also identify locations for mitigation that may not (yet) be significantly impacted. For example, in [1] the method for substrate particle size characterization using a pebble count was adapted from [7,23]. The original procedure defined by these authors required sampling of 100 substrate particles (n = 100) per study reach. However, this process is greatly time consuming and laborious and was therefore modified (n = 15). The consequence was a challenge related to analyzing the collected data (i.e., smaller sample size). Reference [1] found that while reducing the sampling to 15 substrate particles at each survey point reduced the time/labor problem, the sample size was not statistically representative, though remained hydro-ecologically informative. Other methods need to be developed (e.g., photometric) that are applicable in sediment laden streams, and studies must be conducted that identify a balance between labor costs/time and necessary data to inform resource managers. Another example pertains to the presence and size of submerged woody rootmats that provide important refugia for macroinvertebrates and other aquatic biota [21]. Prior to the work of [1,22], there were no standard protocols available to quantify availability and quality of submerged woody root habitat. This method is therefore in need of validation and refinement. Data analyses of PHA/rPHA data comprise other challenges, and a need for standardized methods that balance practitioner expertise and analytical rigor to best guide decision making. Current standard statistical methods include (but are not limited to) descriptive statistics, smoothing (e.g., averaging, moving windows, etc.), analysis of variance, and post-hoc multiple comparisons. Other analyses, however, need to be used (or developed) to best understand the interacting complexities of multiple indices (e.g., multiple regression, multivariate analysis, trend analysis, time series analysis, etc.). Considering the ultimate goal of physical habitat assessment is to improve understanding of ecosystem structure, response, function, and other factors contributing to all of the above, statistical methods need to be identified that improve predictions but do not ignore natural variability or hydro-ecological anthropogenic effects that may, or may not, be statistically significant, yet are important for responsible land management decisions.

3.1.4. Challenges of Legacy Effects

The hydro-ecological and geomorphological influences of historic land use practices are typically overlooked when making land management decisions [41]. The issue is exacerbated by a lack of record and increasing reliance on publicly available datasets that do not include information concerning historic land cover conversion or structural landscape changes pre-dating contemporary records [42].

It is therefore critical to include a thorough investigation of historic practices with any rPHA, given that most contemporary watershed conditions reflect not only current but also historic practices in more or less equivalent proportions. From a geomorphological/aquatic ecological perspective, a lack of attention to potential legacy effects is problematic, since an accurate conception of the response of a stream to natural and anthropogenic pressures requires accounting for all contributing factors (e.g., hydroclimate regime, natural landscape evolution, past and present ecosystem disturbances). Despite widespread agreement within the scientific community regarding the persistence of legacy effects on ecosystem function [42–44], many stream monitoring, mitigation, and restoration efforts remain short-sighted [41]. Specifically, it is common, and perhaps logical, for stream habitat research to focus on current stressors as potentially responsible for currently observed degradation. In contemporary developed watersheds, urbanization is often identified and highlighted as the primary mode of anthropogenic disturbance of stream ecosystems [41]. However, alternative land use practices have been shown to yield persistent hydrologic regime effects [45–47]. These practices are easily overlooked after discontinuation of the practice (e.g., forest removal, agricultural cultivation). For example, upland soil erosion due to agriculture can result in sediment deposition in floodplains and stream channels [48,49]. However, it is estimated that the effects of historic land use practices that generated excess sediment supply to floodplains and stream channels (e.g., agriculture) can persist for millennia as floodplain streambanks gradually erode and sediment is transported downstream [48]. In addition to historic land use practices, natural landscape evolution may constitute an unrecognized legacy effect. As such processes typically pre-date instrumental records, they are poorly understood and rarely considered. For example, Reference [41] presented a case study of a U.S. Midwestern stream system (a tributary of the Missouri River) where urban and residential development in the lower watershed is potentially masking the hydrologic impacts of natural head-cutting from the Missouri River, a process occurring since the end of the Pleistocene Glaciation [50,51]. Presumably, many mixed-land-use watersheds have a land use history and a hydrologic system evolution that pre-dates instrumentation records. In the absence of due diligence regarding legacy land use practices and natural geomorphic evolution, stream habitat research and restoration efforts risk being confounded by unrecognized contributing factors, and consequently may comprise obtuse attempts to characterize and address only observed/observable problems. Investigation(s) of legacy effects of land use practices in any managed watershed is therefore imperative and a critical challenge.

4. Conclusions

It can be challenging to link hydro-ecological impairment to specific land use types in contemporary, mixed-land-use watersheds comprising urban, rural, agricultural, and forest cover (and other land uses). Recent research has demonstrated the capacity of stream physical habitat assessments (PHA) to produce information that, when paired with land use data, may reveal causal patterns in aquatic physical habitat degradation, and help resource managers identify potential stream reaches for rehabilitation or restoration in these complex systems. However, a great deal of work is necessary to validate the potential of PHA to document fine-scale incremental change in physical habitat conditions. While there are many additional aspects of land use rPHA investigations and analyses not represented here (e.g., linking land use activities in-stream biota, etc.), specific challenges and research needs identified in this article include, (a) field-based validation and methodological optimization of new remote sensing and geospatial information systems technologies, (b) challenges in vegetation survey methods, (c) refinement of analytical methods, and (d) consideration of legacy land use impacts and hydrologic system evolution during rPHA design and results interpretation. Such challenges and needs constitute timely, high-impact research opportunities for investigators from a wide variety of fields. Given the potential of rPHA to advance water resource management through hydro-ecological observations, and to substantially reduce costs in so-doing, improvements to the methods and integrated technologies will further increase efficiencies and aid in utilizing federal, state, and other tax dollars most effectively. Considering the unique obstacles currently hampering successful water resource management in many contemporary watersheds globally (e.g., climate change, land use intensification/complexity, financial limitations, competing stakeholder groups, human population growth, etc.), novel methods for evaluating aquatic ecosystem function/disturbance that can rapidly provide accurate data at reduced investment are urgently needed. Physical habitat assessment (including rPHA) is an invaluable option for meeting such demands, and will increase in usefulness as the methods are improved and refined by scientific and practitioner communities.

Acknowledgments: This work was supported by the National Science Foundation under Award Number OIA-1458952, the USDA Natural Resources Conservation Service (NRCS) and West Virginia University. Results presented may not reflect the views of the sponsors and no official endorsement should be inferred. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Special thanks are due to many scientists of the Interdisciplinary Hydrology Laboratory (www.forh2o.net).

Author Contributions: Jason A. Hubbart conceived and designed the article; Jason A. Hubbart, Elliott Kellner, Paul Kinder and Kirsten Stephan wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hooper, L.; Hubbart, J.A. A rapid physical habitat assessment of wadeable streams for mixed-land-use watersheds. *Hydrology* **2016**, *3*, 37. [CrossRef]
2. Maddock, I. The importance of physical habitat assessment for evaluating river health. *Freshw. Biol.* **1999**, *41*, 373–391. [CrossRef]
3. Allan, J.D. Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annu. Rev. Ecol. Evol. Syst.* **2004**, *35*, 257–284. [CrossRef]
4. Montgomery, D.R.; Buffington, J.M. Channel-reach morphology in mountain drainage basins. *Geol. Soc. Am. Bull.* **1997**, *109*, 596–611. [CrossRef]
5. Thomson, J.R.; Taylor, M.P.; Fryirs, K.A.; Brierley, G.J. A geomorphological framework for river characterization and habitat assessment. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2001**, *11*, 373–389. [CrossRef]
6. Allan, D.; Erickson, D.; Fay, J. The influence of catchment land use on stream integrity across multiple spatial scales. *Freshw. Biol.* **1997**, *37*, 149–161. [CrossRef]
7. Wolman, M.G. A cycle of sedimentation and erosion in urban river channels. *Geogr. Ann. Ser. A Phys. Geogr.* **1967**, *49*, 385–395.
8. Paul, M.J.; Meyer, J.L. Streams in the urban landscape. *Ann. Rev. Ecol. Syst.* **2001**, *32*, 333–365. [CrossRef]
9. Poff, N.L.; Bledsoe, B.P.; Cuhaciyan, C.O. Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. *Geomorphology* **2006**, *79*, 264–285. [CrossRef]
10. Booth, D.B. Urbanization and the natural drainage system–impacts, solutions, and prognoses. *Northwest Environ. J.* **1991**, *7*, 93–118.
11. Walsh, C.J.; Roy, A.H.; Feminella, J.W.; Cottingham, P.D.; Groffman, P.M.; Morgan, R.P. The urban stream syndrome: Current knowledge and the search for a cure. *J. N. Am. Benthol. Soc.* **2005**, *24*, 706–723. [CrossRef]
12. Vietz, G.J.; Walsh, C.J.; Fletcher, T.D. Urban hydrogeomorphology and the urban stream syndrome: Treating the symptoms and causes of geomorphic change. *Prog. Phys. Geogr.* **2016**, *40*, 480–492. [CrossRef]
13. Hopkins, R.L.; Altier, B.M.; Haselman, D.; Merry, A.D.; White, J.J. Exploring the legacy effects of surface coal mining on stream chemistry. *Hydrobiologia* **2013**, *713*, 87–95. [CrossRef]
14. Fritz, K.M.; Fulton, S.; Johnson, B.R.; Barton, C.D.; Jack, J.D.; Word, D.A.; Burke, R.A. Structural and functional characteristics of natural and constructed channels draining a reclaimed mountaintop removal and valley fill coal mine. *J. N. Am. Benthol. Soc.* **2010**, *29*, 673–689. [CrossRef]
15. Booth, D.B.; Jackson, C.R. Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. *J. Am. Water Resour. Assoc.* **1997**, *33*, 1077–1090. [CrossRef]
16. Mažeika, S.; Sullivan, P.; Watzin, M.C.; Hession, W.C. Understanding stream geomorphic state in relation to ecological integrity: Evidence using habitat assessments and macroinvertebrates. *Environ. Manag.* **2004**, *34*, 669–683. [CrossRef] [PubMed]

17. Kellner, E.; Hubbart, J.A. Advancing understanding of the surface water quality regime of contemporary mixed-land-use watersheds: An application of the experimental watershed method. *Hydrology* **2017**, *4*, 31. [CrossRef]
18. Zeiger, S.; Hubbart, J.A. Quantifying flow interval—Pollutant loading relationships in a rapidly urbanizing mixed-land-use watershed of the central US. *Environ. Earth Sci.* **2017**. [CrossRef]
19. Zeiger, S.; Hubbart, J.A. A SWAT model validation of nested-scale contemporaneous stream flow, suspended sediment and nutrients from a multiple-land-use watershed of the central USA. *Sci. Total Environ.* **2016**, *572*, 232–243. [CrossRef] [PubMed]
20. Bernhardt, E.S.; Palmer, M.A. River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecol. Appl.* **2011**, *21*, 1926–1931. [CrossRef] [PubMed]
21. Rabení, C.F.; Doisy, K.E.; Zweig, L.D. Stream invertebrate community functional responses to deposited sediment. *Aquat. Sci.* **2005**, *67*, 395–402. [CrossRef]
22. Nichols, J.R. Macroinvertebrate Assemblage Composition along a Longitudinal Multiple-Land-Use Gradient in a Midwestern Stream. Master's Thesis, University of Missouri, Columbia, MO, USA, 2012; p. 104.
23. Peck, D.V.; Herlihy, A.T.; Hill, B.H.; Hughes, R.M.; Kaufmann, P.R.; Klemm, D.J.; Lazorchak, J.M.; McCormick, F.H.; Peterson, S.A.; Ringold, P.L.; et al. *Environmental Monitoring and Assessment Program-Surface Waters Western Pilot Study: Field Operations Manual for Wadeable Streams*; US Environmental Protection Agency, Office of Research and Development: Washington, DC, USA, 2006.
24. Fitzpatrick, F.A.; Waite, I.R.; D'Arconte, P.J.; Meador, M.R.; Maupin, M.A.; Gurtz, M.E. *Revised Methods for Characterizing Stream Habitat in the National Water-Quality Assessment Program*; U.S. Geological Survey: Reston, VA, USA, 1998; p. 77.
25. Bockelmann, B.N.; Fenrich, E.K.; Lin, B.; Falconer, R.A. Development of an ecohydraulics model for stream and river restoration. *Ecol. Eng.* **2004**, *22*, 227–235. [CrossRef]
26. Piégay, H.; Schumm, S.A. Systems approach in fluvial geomorphology. In *Tools in Fluvial Geomorphology*; Kondolf, G.M., Piégay, H., Eds.; John Wiley and Sons: Chichester, UK, 2003; pp. 105–135.
27. Elliott, C.M.; Huhmann, B.L.; Jacobson, R.B. *Geomorphic Classification of the Lower Platte River*; U.S. Geological Survey: Lincoln, NE, USA, 2009; p. 29.
28. Jacobson, R.B.; Johnson, H.E., III; Reuter, J.M.; Panfil-Wright, M.; Johnson, H.E. *Physical Aquatic Habitat Assessment Data, Ozark Plateaus, Missouri and Arkansas*; U.S. Geological Survey: Lincoln, NE, USA, 2004. Available online: http://pubs.er.usgs.gov/usgspubs/ds/ds94 (accessed on 1 November 2017).
29. Li, A.; Wang, A.; Liang, S.; Zhou, W. Eco-environmental vulnerability evaluation in the mountainous region using remote sensing and GIS—A case study in the upper reaches of the Minjiang River, China. *Ecol. Model.* **2006**, *192*, 175–187. [CrossRef]
30. Ma, Y. GIS application in watershed management. *Nat. Sci.* **2004**, *2*, 1–7.
31. Pandey, A.; Chowdary, V.M.; Mal, B.C. Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. *Water Resour. Manag.* **2007**, *21*, 729–746. [CrossRef]
32. Dietrich, J.T. Riverscape mapping with helicopter-based structure-from-motion photogrammetry. *Geomorphology* **2016**, *252*, 144–157. [CrossRef]
33. Hall, R.K.; Watkins, R.L.; Heggem, D.T.; Jones, K.B.; Kaufmann, P.R.; Moore, S.B.; Gregory, S.J. Quantifying structural physical habitat attributes using LIDAR and hyperspectral imagery. *Environ. Monit. Assess.* **2009**, *159*, 63–83. [CrossRef] [PubMed]
34. Woodget, A.S.; Carbonneau, P.E.; Visser, F.; Maddock, I.P. Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. *Earth Surf. Process. Landf.* **2015**, *40*, 47–64. [CrossRef]
35. Hogan, S.D.; Kelly, M.; Stark, B.; Chen, Y. Unmanned aerial systems for agriculture and natural resources. *Calif. Agric.* **2017**, *71*, 5–14. [CrossRef]
36. Lemmon, P.E. A New Instrument for measuring forest overstory density. *For. Sci.* **1957**, *2*, 314–320.
37. Coulloudon, B.; Podborny, P.; Eshelman, K.; Rasmussen, A.; Gianola, J.; Robles, B.; Habich, N.; Shaver, P.; Hughes, L.; Spehar, J.; et al. *Sampling Vegetation Attributes*; Bureau of Land Management: Denver, CO, USA, 1999; p. 164.
38. Winward, A. *Monitoring the Vegetation Responses in Riparian Areas*; Gen. Tech. Rep. RMRS-GTR-47. Ogden, UT; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2000; p. 49.

39. Overton, C.; Wollrab, S.; Roberts, B.; Radko, M. *R1/R4 (Northern/Intermountain Regions) Fish and Fish Habitat Standard Inventory Procedures Handbook*; Gen. Tech. Rep. INT-GTR-346; Department of Agriculture, Forest Service, Intermountain Research Station: Ogden, UT, USA, 1997; p. 73.
40. WVDEP (West Virginia Department of Environmental Protection). *Watershed Assessment Branch 2015 Field Sampling Standard Operating Procedures*; Division of Water and Waste Management, Watershed Assessment Branch: Charleston, WV, USA, 2015. Available online: http://www.dep.wv.gov/WWE/watershed/Pages/WBSOPs.aspx (accessed on 15 September 2017).
41. Kellner, E.; Hubbart, J.A. Confounded by forgotten legacies: Effectively managing watersheds in the contemporary age of unknown unknowns. *Hydrol. Process. Today* **2017**, 1–10. [CrossRef]
42. Bain, D.J.; Green, M.B.; Campbell, J.L.; Chamblee, J.F.; Chaoka, S.; Fraterrigo, J.M.; Sobczak, W.V. Legacy effects in material flux: Structural catchment changes predate long-term studies. *Bioscience* **2012**, *62*, 575–584. [CrossRef]
43. Foster, D.; Swanson, F.; Aber, J.; Burke, I.; Brokaw, N.; Tilman, D.; Knapp, A. The importance of land-use legacies to ecology and conservation. *Bioscience* **2003**, *53*, 77–88. [CrossRef]
44. Walter, R.C.; Merritts, D.J. Natural streams and the legacy of water-powered mills. *Science* **2008**, *319*, 299–304. [CrossRef] [PubMed]
45. Kellner, E.; Hubbart, J.A.; Ikem, A. Comparing forest and agricultural shallow groundwater chemical status a century after harvest. *Sci. Total Environ.* **2015**, *529*, 82–90. [CrossRef] [PubMed]
46. Kellner, E.; Hubbart, J.A. Agricultural and forest land use impacts on floodplain shallow groundwater temperatures. *Hydrol. Process.* **2016**, *30*, 625–636.
47. Kellner, E.; Hubbart, J.A. A Comparison of the spatial distribution of vadose zone water in forested and agricultural floodplains a century after harvest. *Sci. Total Environ.* **2016**, *542*, 153–161. [CrossRef] [PubMed]
48. Jackson, C.R.; Martin, J.K.; Leigh, D.S.; West, L.T. A southern piedmont watershed sediment budget: Evidence for a multi-millenial agricultural legacy. *J. Soil Water Conserv.* **2005**, *60*, 298–310.
49. Trimble, S.W. Fluvial processes, morphology and sediment budgets in the Coon Creek Basin, WI, USA, 1975–1993. *Geomorphology* **2009**, *108*, 8–23. [CrossRef]
50. Tarr, W.A. Intrenched and incised meanders of some streams on the northern slope of the Ozark Plateau in Missouri. *J. Geol.* **1924**, *32*, 583–600. [CrossRef]
51. Kellner, E.; Hubbart, J.A. Application of the experimental watershed approach to advance urban watershed precipitation/discharge understanding. *Urban Ecosyst.* **2016**. [CrossRef]