Hinkson Creek Collaborative Adaptive Management Science Strategy

Draft May 4, 2018

Hinkson Creek Science Team

Purpose of this Document

This document presents a summary of the current state of knowledge of Hinkson Creek science, a discussion of some of the major scientific questions yet to be resolved, and discussion of the challenges in addressing those uncertainties. The intention is to provide a road map for developing the information needed to support Hinkson Creek stakeholders' decision processes.

The *fundamental objective* of the Hinkson Creek Collaborative Adaptive Management (CAM) process is to implement the Hinkson Creek TMDL and improve Hinkson Creek, with the ultimate goal of having the creek meet all applicable water-quality standards (Hinkson Creek Collaborative Adaptive Management Partners, 2012). Although the CAM document also notes *means objectives* that include improving diversity of invertebrate communities, ecosystem health, and general water quality, the focus articulated by stakeholders is to remove the creek's impaired status. Removing the impaired status – and keeping impaired status from returning – depends on improving understanding of the processes at work in the watershed through the application of scientific knowledge and techniques.

The CAM agreement indicates that the purpose of the Science Team is:

> *"…to identify, evaluate and advance the necessary scientific studies needed to support the collaborative adaptive management processes described herein. The Science Team will coordinate monitoring and modeling for Hinkson Creek related to the collaborative adaptive management process. This team will respond to inquiries from and make recommendations to the Stakeholder Committee. The Science Team is responsible for understanding available scientific information that is applicable to the questions at hand, selecting the best and most relevant information, and synthesizing it into reports for the Stakeholder Committee."*

Within time and funding constraints the Science Team has defined its primary roles as evaluating potential factors contributing to the impairment of Hinkson Creek, evaluating the optimum application of science to resolve uncertainties, determining the efficacy of actions that would improve water quality conditions, and advising Stakeholders and the Action Team on science strategies. The recommendations in this document are intended to provide the Stakeholders with the information needed to make informed decisions about investment in science, based on what is known, what is not known, and what needs to be known to satisfy their risk tolerance.

The Science Team believes this document is critical at this specific time in the Hinkson Creek CAM process. There has been significant turnover in membership in the Stakeholder, Action, and Science teams and institutional memory of the intent of the science effort is at risk of being lost. The CAM agreement emphasizes the role of scientific uncertainties as a motivation for adaptive management: *"CAM is a stakeholder-based adaptive management process for decision-making, dealing with the scientific and socioeconomic complexities and uncertainties inherent in many ecosystems."* The importance of the role of science in addressing uncertainties has been reiterated by many practitioners, including CAMnet (The Collaborative Adaptive Management Network, http://adaptivemanagement.net/): *"A collaborative adaptive management approach incorporates and links knowledge and credible science with the experience and values of stakeholders and managers for more effective management decision-making."*

Within this understanding of CAM, the role of science is to provide the knowledge and credible science so stakeholders can make effective decisions. Although this perspective places science in a supporting role, scientists take on substantial responsibility to assure that the science has the attributes needed by decision makers --- credibility, relevance, and legitimacy (Cash and others, 2003). Central to this responsibility is the assurance that science investments provide information that is relevant to decisions. The objective of this document is to affirm a strategy to provide decision-relevant science.

The CAM process is fundamentally linked to science as it acknowledges the significant uncertainties or unknowns about complex systems and the need to reduce those uncertainties to provide the greatest opportunity for success. As the Hinkson Creek CAM process reaches the 5-year milestone it is an appropriate time to review the state of understanding, review the most pressing scientific questions, examine the role of science in the CAM process, and plot a way forward.

Adaptive management is a multistep process that can usually be viewed in an iterative, circular framework (Williams and others, 2007). The concept of "learning by doing" is implicit in the *implement – monitor – evaluate – adjust* steps (fig. 1).

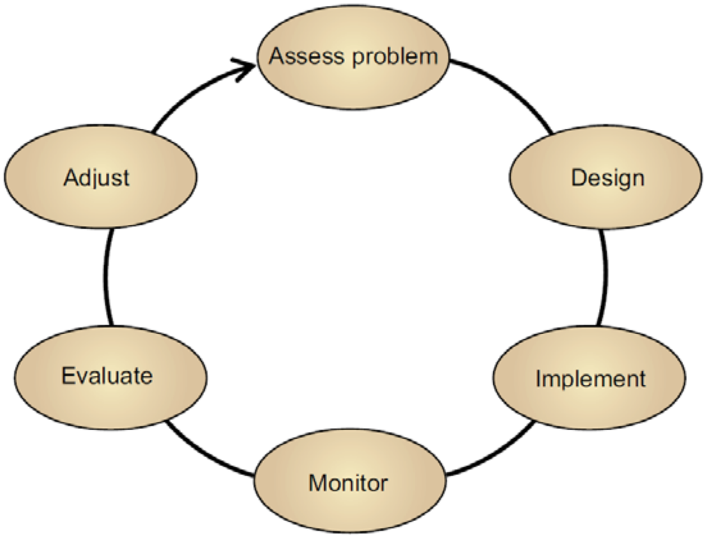

Figure 1. Adaptive-management cycle, from Williams and others (2007).

Within the adaptive-management cycle, however, science is particularly important in the "*Assess problem*" stage because if the problem is not understood, mitigations cannot begin to be designed to address the problem. As Hinkson Creek was originally listed for unknown causes, it is not surprising that assessing the problem has been a central concern of the Science Team. Science is also important within the adaptive-management cycle in design of management experiments, developing effective monitoring, evaluating results, and recommending adjustments. But if the problem is not adequately assessed, the remainder of the adaptive-management cycle cannot be effectively implemented.

We emphasize that although a great deal of progress has been made in the Hinkson Creek CAM process, and in Hinkson Creek science, substantial uncertainty persists about the cause(s) and the cure(s) for stream impairment. The persistent uncertainty arises from the inherent complexity of watershed ecosystems. Managing a perturbed watershed ecosystem to restore some ecological processes while maintaining the goods and services expected by society (housing, businesses, and infrastructure) is a challenging task.

Background

Hinkson Creek (fig. 2) flows from rural Boone County through the City of Columbia to Perche Creek just upstream of its confluence with the Missouri River. Hinkson Creek was listed as impaired in 1998 for two separate reasons. Hinkson Creek does not support the "protection of aquatic life" designated use as specified in Missouri's Water Quality Standards although no pollutant has been identified that accounts for this assessment. Separately, parts of Hinkson Creek are also listed as impaired for bacteria as measured in the creek. The decision to address bacteria as part of the CAM process came only after nearly three years had passed and thus that topic has received far less attention to date. Bacteria will not be addressed in this strategy document.

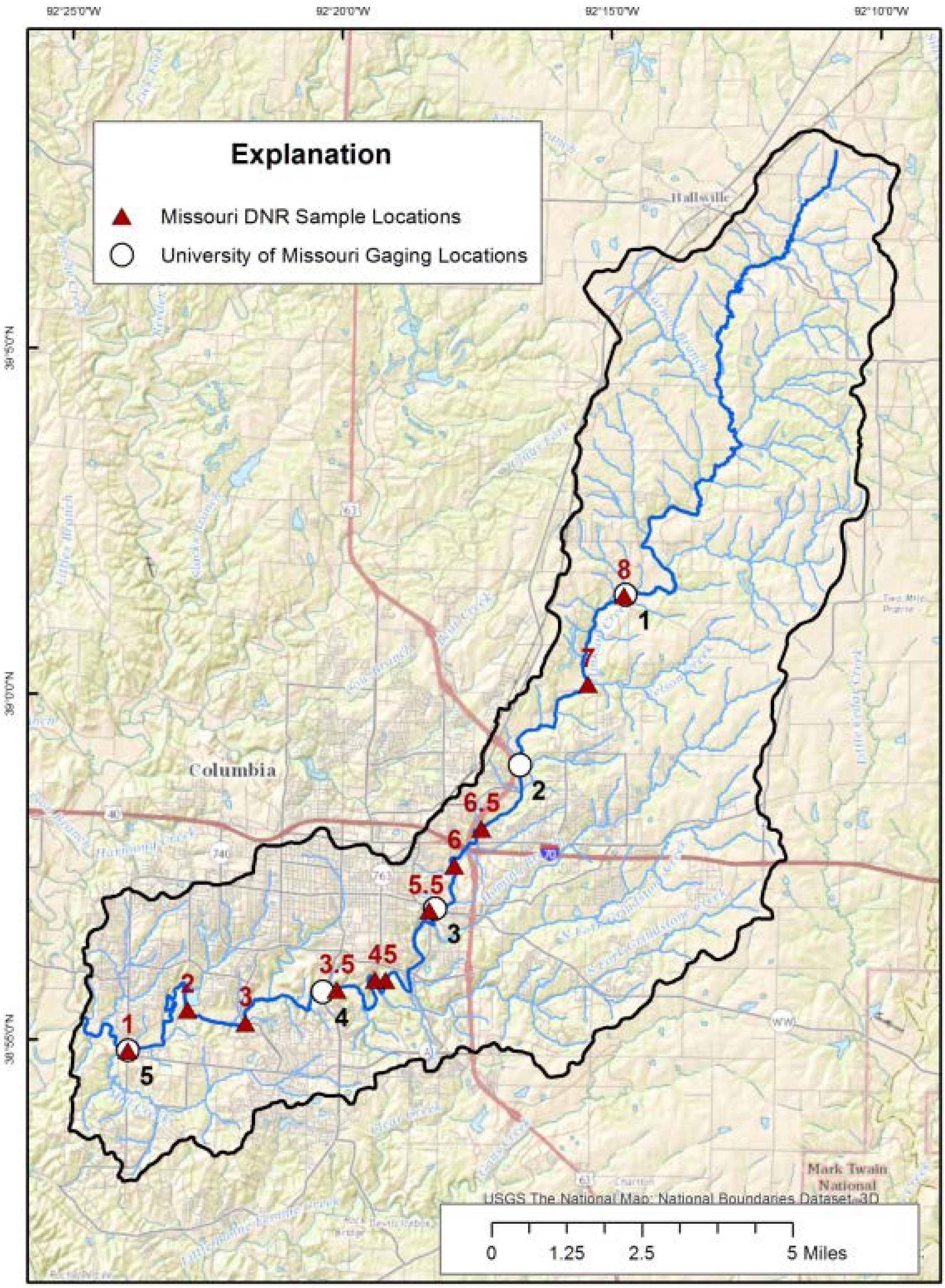

Figure 2. Location map of Hinkson Creek, showing Missouri Department of Natural Resources (DNR) sample locations and University of Missouri stream gaging sites.

Normally, when a stream or other water body is listed as impaired, a Total Maximum Daily Load (TMDL) analysis is completed to define the maximum pollutant load that will allow the stream to return to conditions fully compliant with its designated uses. This approach does not lend itself well to a situation where no specific pollutant has been identified.

In 2012, Boone County, the City of Columbia, the University of Missouri-Columbia, the US Environmental Protection Agency and the Missouri Department of Natural Resources jointly agreed to use a Collaborative Adaptive Management (CAM) approach to address water quality concerns in Hinkson Creek. CAM is a proven tool for use in complex systems with significant scientific unknowns as it expressly provides a framework for learning and putting new knowledge and understanding to use to solve complex challenges. While it has been used in biological restoration efforts, the Hinkson Creek CAM process is its first application to an impaired watershed in lieu of a TMDL.

As part of this agreement, a Science Team was selected to provide advice to the stakeholder committee for the CAM process. This team often works closely with a group that represents the local government agencies, serving as an Action Team focused on engineering, chemical and biological approaches to improve water quality. The Science Team is composed of experts in hydrology, bioassessments, water quality, engineering, geomorphology, and sediment transport. Team members serve as volunteers or their time is contributed by their host institutions. The members of the Science Team work together with the understanding that their advisory role on the Team requires them to maintain independence from the policy goals of their host institutions. While it is impossible to eliminate all potential for perceptions of conflict of interest, the Team relies on the individual scientific integrity of members and the team's jointly held understanding of the value of credibility, relevance, and legitimacy to guide participation. Essentially, Team members agree to take off their institution hat and put on a Team hat while participating. Where this is not possible, members are encouraged to recuse themselves from specific recommendations.

The Missouri Department of Natural Resources (DNR) has conducted invertebrate monitoring at 11 sites since 2012 to track progress in mitigating impairment. The final metric for the invertebrate monitoring is the Macroinvertebrate Stream Condition Index (MSCI) score. The MSCI is a multi-metric score calculated based on macroinvertebrate community attributes, and it is used to assess whether a stream is fully supporting of the beneficial use designation of aquatic life protection as defined in Missouri's Water Quality Standards. Scores compiled through 2015 are promising as they show that the upper part of Hinkson Creek has invertebrate community scores (MSCI ≥16) suggesting that all uses are being supported (table 1). Scores are somewhat lower downstream and are not fulling supporting its designated uses. Taken as a whole, the scores suggest that Hinkson is partially to fully supporting uses. However, there has been no documentation of changes of stream condition that would have led to improved scores, hence no understanding of cause and effect. Understanding of cause and effect is fundamental to CAM because understanding drives decisions and designs. Once the creek complies with water-quality standards, the cause and effect understanding can be used to help maintain water quality to prevent Hinkson Creek from being added to the impaired waters list in the future as the watershed continues to develop.

Table 1. Missouri Stream Condition Index (MSCI) scores by sampling location and date, 2001 - 2014. Cells highlighted have values less than or equal to 14.

	Date of Sample																Averages		
Sample Location	Fall 2001	Spring 2002	Fall 2003	Spring 2004	Spring 2005	Fall 2005	Spring 2006	Spring 2012	Fall 2012	Spring 2013	Spring 2014	Fall 2014	Spring 2015	Fall 2015	Spring 2016	Fall 2016	2001 - 2016	2012 - 2016	2001 - 2006
HC 8		16.0						18.0		14.0	16.0	18.0	16.0		12.0	16.0	15.8	15.7	16.0
HC 7		16.0	18.0	16.0	16.0	18.0		16.0		16.0	14.0	20.0	16.0		14.0	20.0	16.7	16.4	16.8
HC 6.5				16.0				16.0		16.0	14.0	18.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
HC6	12.0		16.0	14.0	18.0	16.0		14.0		16.0	14.0	20.0	16.0	18.0	12.0	12.0	15.2	16.0	15.2
HC 5.5			14.0	16.0	16.0			16.0		16.0	16.0	18.0	12.0	16.0	16.0	14.0	15.5	15.5	15.3
HC 5								16.0		16.0	12.0	20.0	12.0	14.0	16.0	14.0	15.0	15.0	
HC 4		12.0						16.0		16.0	16.0	18.0	14.0	14.0	16.0	14.0	15.1	15.5	12.0
HC 3.5					12.0	12.0		14.0		16.0	16.0	14.0	12.0	16.0	16.0	16.0	14.4	15.0	12.0
HC 3	16.0	12.0					16.0			10.0	12.0	14.0	12.0	16.0	16.0	16.0	14.0	12.0	14.7
HC 2	14.0	12.0					12.0			14.0	12.0	16.0	12.0	16.0	16.0	14.0	13.8	14.0	12.7
HC 1	14.0	14.0					14.0			12.0		14.0	12.0	20.0	16.0	16.0	14.7	13.0	14.0

According to section 11.1 of the Hinkson Creek CAM agreement, the collaborative adaptive management process may reach a logical end when full attainment of Missouri's narrative water quality standards for the protection of aquatic life in Hinkson Creek have been met. The CAM agreement goes on to say that attainment shall be based on conditions outlined in the *Methodology for the Development of the 2012 Section 303(d) List in Missouri* (also known as the Listing Methodology Document, or LMD). The Missouri Department of Natural Resources is required to update the LMD every two years, and all past and present LMDs are available at http://dnr.mo.gov/env/wpp/waterquality/303d/303d.htm.

The LMD provides a detailed description of how streams are evaluated in determining whether to be included on the 303(d) List of Impaired Waters. Conversely, the LMD also provides an explanation of conditions that have to be met for a stream to be excluded from the list; it is this latter condition that the CAM seeks to attain. Table 2 includes pertinent language from Table B-1 in the 2012 LMD as it pertains to Hinkson Creek.

Table 2. Selected portion of Table B-1 from the 2012 Listing Methodology Document.

Beneficial Use	Analytes	Analytical Tool	Decision Rule/Hypothesis	Criterion Used with the Decision Rule	Significance Level
Aquatic Life	Biological Monitoring (narrative)	For DNR Invert protocol and sample sizes greater than 30: Direct comparison.	A direct comparison of frequencies between test and biological criteria reference streams will be made.	Rate as impaired if biological criteria reference stream frequeny of sustaining scores is more than five percent more than test stream.	Not applicable.

For biological criteria reference streams in the Ozark/Moreau/Loutre Ecological Drainage Unit (EDU), the frequency of sustaining scores is 82.6 percent. Based on the Decision Rule in the table above, a minimum of 77.6 percent of Hinkson Creek samples would have to be fully supporting before it could be considered “unimpaired.”

At present, the cause for impairment of Hinkson Creek remains unknown, hence solutions to removing impairment are also unknown. There continues to be a need to invest in scientific information in order to reduce these uncertainties and design effective mitigations. The objective of the science strategy is to focus the science investment on the most relevant questions in order to provide the best return on that investment. Questions of impacts, complexity, and scalability are central to finding robust, cost-effective solutions. These questions can only be addressed through a combination of measurement, modeling, and hypothesis testing.

Conceptual Ecological Models

The Science Team developed a conceptual ecological model (CEM) for assessing Hinkson Creek (fig. 3). The model illustrates a set of driver-stressor-response relations that are thought to apply to the creek. That is, the CEM serves as a graphical map of the multiple hypotheses that need to be considered in understanding how the creek is impaired and how impairment may be mitigated.

The need for a conceptual model is driven by two major scientific factors: the large uncertainty or lack of understanding of the watershed and the complexity of the multiple interactions that may influence the invertebrate community and the stream’s health. The CEM also shows the potential interactions of any given management action with other ecological and socio-economic processes in the watershed.

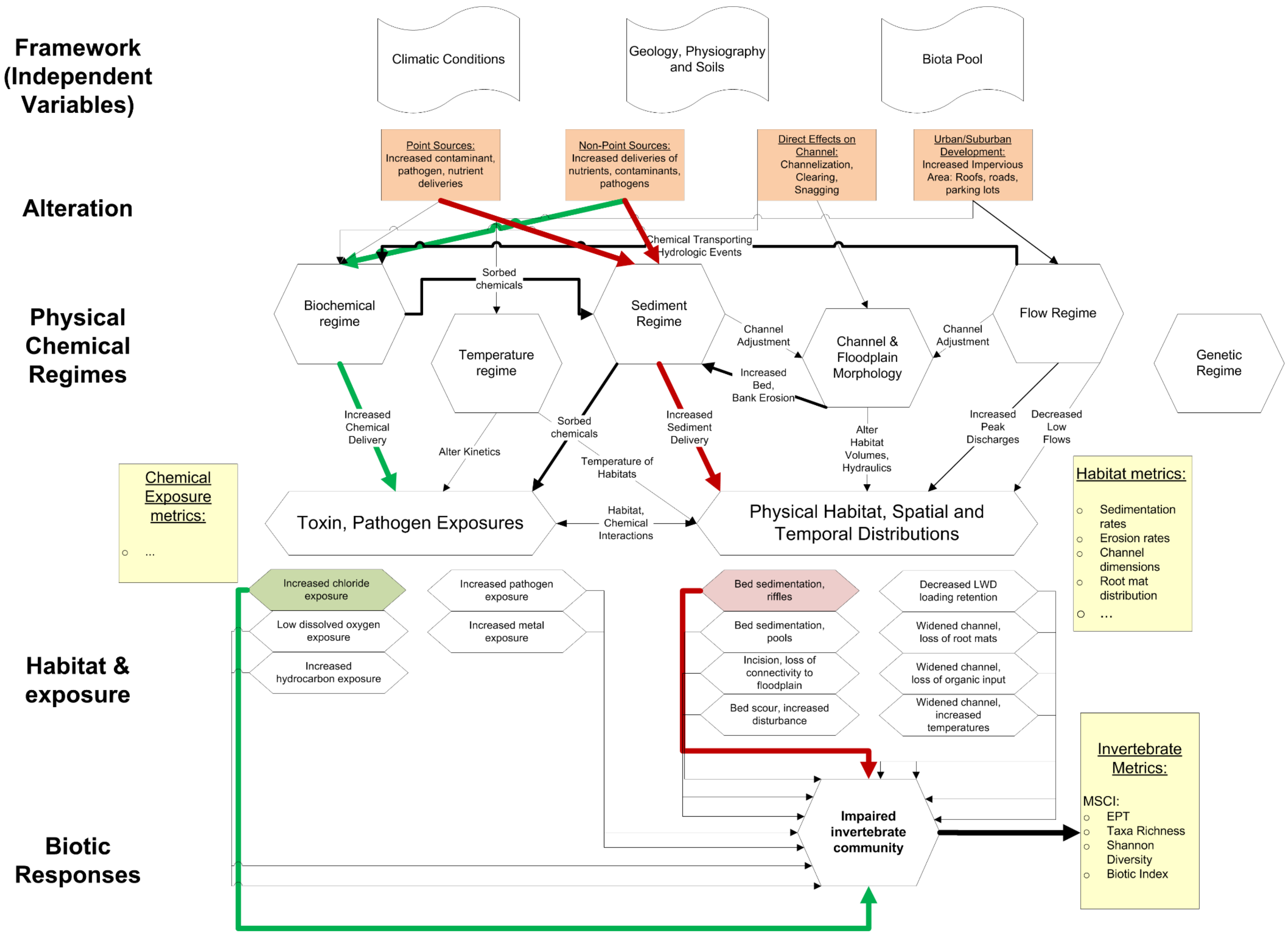

Figure 3. Conceptual ecological model for Hinkson Creek, with emphasis on two hypothetical pathways. Chloride contamination is in green and sediment delivery is in red.

This CEM serves as a framework for understanding how the Hinkson Creek watershed works. The CEM is hierarchical from top to bottom, with independent variables at the top and dependent at the bottom. The highest level recognizes the physical framework of Hinkson Creek – soils, physiography, and climate – independent factors that are resistant to change over management time frames. The alteration level indicates changes in the drainage basin and riparian zone that are likely to affect stream processes. Arrows indicate how changes affect physical and chemical regime of the river, and how these changes may propagate to habitat, exposures, and endpoints comprised of stream biota and human interests. The CEM structure reflects the current thinking of the Science Team (and is by definition amenable to change as new information is developed). The present structure divides potential pathways to impairment between chemical and physical, although with noteworthy interactions between the two. This dichotomy is fundamental to understanding of impairment because chemical and physical stresses are likely to arise from very different watershed alterations and processes. Moreover, approaches and costs for mitigation of physical and chemical stresses are likely to be very different.

State of the science on Hinkson Creek

As part of the CAM agreement, the DNR agreed to a minimum of three years of invertebrate data collection and analysis at 11 sites within Hinkson Creek. These data are central to assessing the status of the creek relative to water quality standards. Invertebrate communities respond to a broad array of conditions and stressors and thus provide an integrative measure of an important “response variable,” one that reflects conditions, but may not, by itself, provide much insight into the *causes* of the trends observed. These data show that Hinkson Creek as a whole is not fully meeting water quality standards, but suggest that parts of the creek are doing so and others are not far from doing so (table 1). These data suggest that Hinkson is not a lost cause and that actions could be taken to improve the creek. The seasonal, annual and geographic variability seen in these data and their dependence on many environmental variables strongly support the use of CAM to address Hinkson Creek.

It is important to emphasize that understanding of cause/effect linkages is necessary to understand impairment, and to design and implement mitigations. Invertebrate communities may vary over time and space and may at some point improve to a level that would support delisting. But if the cause for the variation is not understood, there will be little basis for confidence that improvement can be maintained, especially as development continues in the watershed.

Foundational science projects

Missouri Department of Natural Resources assessments

The Missouri Department of Natural Resources (DNR) has developed background science information on Hinkson Creek since 2003. Phase I of DNR studies during fall 2001 and spring 2002 involved the water quality triad consisting of assessment of the aquatic community, chemical analyses, and toxicity testing (Missouri Department of Natural Resources, 2004). The Phase I studies confirmed that the aquatic community was impaired between Interstate 70 and Broadway and potentially downstream from Broadway. The toxicity tests indicated that some storm water discharges were toxic to test organisms; implicated chemicals were polycyclic aromatic hydrocarbons (PAHs), pesticides, petroleum compounds, and metals. The studies also documented high levels of sodium and calcium chloride in snowmelt samples, and instream toxicity was established for one snowmelt event. Toxicity effects in this event were concentrated near the former Missouri Department of Transportation salt storage facility and the Conley Road shopping center. Bacteria (*E. coli*) counts exceeding recommended levels were also documented but the source for bacteria was not determined. The survey also noted increased sedimentation in the impaired segment compared to the local control stream Bonne Femme Creek, and that sedimentation increased from upstream to downstream. The report also noted that the duration of turbidity in Hinkson Creek was longer than that in Bonne Femme Creek and that prominent gully incision was associated with storm water discharge points.

Phase II studies (July 2004 – June 2005) found elevated turbidity (during low flow and associated with the US Highway 63 connector), elevated low-flow chloride values, sporadic toxicity, and community metrics that showed some improvement compared to Phase I (Missouri Department of Natural Resources, 2005). Nevertheless, Phase II biological samples documented urban effects, including an increase in tubificid worms in some sections.

Phase III studies (Fall 2005 - June 2006) extended assessments downstream to the confluence with Perche Creek (Missouri Department of Natural Resources, 2006). The macroinvertebrate data indicated that sites in the urban parts of Hinkson Creek continued to be impaired (partially supporting). Base flow chloride concentrations in the lower sections of the creek were higher than those measured in the upper sections and particularly high concentrations were measured in Flat Branch (283 mg/L compared to EPA chronic criterion of 230 mg/L). Dissolved oxygen (DO) measurements during this study linked low DO to warm, dry periods when pools became stagnant.

Following the three phases of the initial study, Missouri DNR continued fall and spring sampling 2012 – 2016. As of this date, the MSCI scores are available through fall of 2015 (table 1). Note that the data in table 1 summarize a great deal of taxonomic and contextual data for this sampling program into one metric; a substantial amount of additional information is available for the individual components of the MSCI. The heavy horizontal line in table 1 is a general boundary between upstream sites that have, on average, supporting MSCI scores greater than 14 and downstream sites that are generally characterized by partially-supporting scores.

Physical context assessments

The conceptual model and knowledge of studies in other urbanizing watersheds led to the decision to recommend a 2-part habitat assessment to the stakeholder committee. The objectives of the assessment were 1) quantify the spatial framework of Hinkson Creek, including “hard” factors that are not amenable to change, such as structure of the stream network, large infrastructure, bedrock geologic controls, and hydraulic effects of the Missouri River, and 2) to explore whether spatial distributions of some physical habitat features could provide insight into the sources of stress and impairment. An example of the latter is whether the distribution of sedimentation in the creek would be concentrated downstream from tributaries with specific land uses or sources of disturbance.

The first part of the study (Missouri Resource Assessment Partnership, 2013) used remotely sensed data to provide an overview of the fundamental physical parameters of the watershed, compiled in geographic information system (GIS) context. The second part (Hooper, 2015) was a detailed, field-based longitudinal assessment of Hinkson Creek that provided a wealth of data on the basic form and structure of the creek and its floodplain. This assessment produced a framework especially well-suited for designing additional studies for examining the creek at a finer scale. It also provides information necessary to understand the scalability of certain specific actions under consideration.

Several key findings came from the two foundational assessments. One is understanding of the range of physical variation of Hinkson Creek and how that variation interacts with stream processes. Some physical factors in the watershed can be viewed as independent variables – like types and distributions of soils and bedrock, the stream channel network, and much of the physical infrastructure. We do not expect those things to change and they determine a lot of the biophysical capacity of the watershed. Climatic influences are also mostly independent [although see Hubbart and others (2014a) about urban heat-island effect] and subject to non-stationarity. Land use and land cover also are treated as independent variables although they can be influenced through management decisions.

Other factors that were quantified in the GIS and field assessments can be considered dependent or response variables, depending on time frame of consideration. For example, channel sinuosity, channel position, interaction of the channel with bedrock in the valley wall, channel slope, and bankfull channel width and depth are all adjustable geomorphic variables over time frames of seasons to centuries, and therefore can be evaluated as characteristics that might change in response to independent drivers like land-use, land-cover, and climate. On the other hand, when evaluating invertebrate assemblages, these physical variables are typically treated as independent. That is, one expects the biota to respond to variation in the physical variables. Both physical assessments document variables that can be considered independent or dependent; confusion can arise if analyses are not clear about the hypothesized roles.

The GIS assessment documented methodologies for delineating channel and valley dimensions from LiDAR elevation data collected in 2009; this documentation may be useful for future change analysis based on 2015 LiDAR. The analysis confirmed the upstream-downstream gradient of land uses from agricultural to suburban to urban. The analysis also documented substantial longitudinal variation in channel widths, channel sinuosity, valley width, and channel interactions with the valley wall. Channel width may be useful as a dependent variable indicating sources of disturbance and interaction with the valley wall will be useful as an indicator of where channel adjustments are controlled by bedrock and where stream habitats may be influenced by bedrock type and delivery of large substrate from adjacent slopes.

The field-based physical habitat assessment provided important insights about physical characteristics that could not be captured in the GIS analysis because of scale limitations. The longitudinal assessments of physical habitat variables reveal trends at varying scales. Trends of many variables over the entire 56 km of Hinkson Creek are notably interrupted by anomalies measured in several to tens of km. In addition, the high resolution of the data (100 m intervals) also documents anomalies on the order of 100 to several hundred meters. These anomalies may be evidence of specific disturbances. Specific insights are:

- Most of the Hinkson Creek channel starting 26 km downstream of the headwaters is adjacent to bedrock on one bank or both.
- Although channel widths predictably increase in the downstream direction, the trend is interrupted by anomalies of narrower channel between Nelson Creek and Grindstone Creek. The channel narrows again from the Flat Branch confluence to the Perche Creek confluence. These anomalies may be related to bedrock and backwater influences, respectively.
- Bank height and thalweg depth similarly show broad increasing trends in the downstream direction, but are interrupted by anomalies that may indicate fundamental, extrinsic controls on channel processes.
- Channel sinuosity is fairly constant in the upstream 2/3 of the watershed, with values rarely spiking above 1.5. In the lower 1/3 of the watershed sinuosity magnitude and variability increase markedly.
- Canopy cover shows broad trends of decrease from the headwaters to a minimum near the confluence with Hominy Branch, followed by a broad trend of increasing cover in the downstream direction. Within those broad trends, canopy cover is notable for extremely high-frequency variability along the channel.
- Pebble counts in the thalweg documented that Hinkson Creek is dominated by mud (silt + clay particles, < 0.06 mm) and sand (0.06 – 2 mm). Coarser materials (gravel through boulders) increase downstream of Varnon Branch and occur in broad, patchy distribution through the confluence with County House Branch. Downstream of County House Branch coarse sediment is rare, which likely relates to backwater effects from the Missouri River. Bedrock and boulders occur mostly in the middle reaches of Hinkson Creek from upstream of Nelson Creek to just downstream of Flat Branch.
- Embeddedness of fine sediment into gravel or cobble interstices is high at the headwaters and at the downstream section, with a minimum between Nelson and Grindstone Creeks. Embeddedness is thought to be particularly important as a stressor on invertebrate communities in riffle habitats; this distribution may indicate a trend in habitat degradation directly relatable to invertebrate assemblages.
- The distributions of root mat numbers and volume reflect broad trends of peaks associated with confluences of Vernon Branch and Nelson Creek, followed by a minimum of numbers in reaches associated with Hominy Branch and Grindstone Creek. Because root mat volume stays relatively high in this area, it is reasonable to assume that root mats are fewer but larger. Downstream from Flat Branch numbers of root mat stay fairly constant but volume is highly variable, and around the Flat Branch confluence, volumes are some of the highest measured. Because root mats are key habitats for some invertebrates, root mat distributions may be highly influential in macroinvertebrate distributions. Moreover, because root mats are a sampling stratum for DNR invertebrate collections, their distribution may have a strong influence on stream condition scores.
- Related to root mats, the physical survey also evaluated the width of the riparian zone and the longitudinal distribution of woody vegetation on banks. Overall, over 80% of the stream had riparian corridors > 20 width, although more than 75% of the banks themselves had less than 40% vegetative cover. This combination of observations is owed to the definition of riparian corridor used which included any non-developed land.
- At the top of the banks, the distribution of woody vegetation was surprising in that it increased steadily in the downstream direction from about 10% in the headwaters to a peak of near 100% just upstream from the Hominy Branch confluence. Woody vegetation percent stayed, on average, above 50% downstream to the Flat Branch confluence, and then decreased to near 10% at the confluence with Perche Creek.

The complex and sometimes surprising longitudinal relations documented in the field assessment have yet to be completely analyzed and understood. A fertile area for information growth is to place understanding gained from the process science projects discussed in the next section, in the spatial context of the physical assessments.

Social context assessment

The concept that Hinkson Creek should be fishable and swimmable, beyond the letter of the Clean Water Act, implies that people value and use the creek for those purposes, or would if they felt it was safe to do so. Public perceptions and values are therefore a key to determining how ecological values in Hinkson Creek might translate to socio-economic values and public support. A study of awareness and attitudes about water quality documented several interesting trends among Hinkson Creek residents (Baumer, 2007). One of particular importance was the lack of understanding of the term "non-point-source pollution" among the majority of study respondents. This may reflect a prevailing understanding that pollution continues to be dominantly an end-of-pipe problem, with the implication that the population does not understand the difficulties of identifying and quantifying non-point sources. Although the majority of respondents identified development as an environmental concern in the watershed, 30% did not know that Hinkson Creek was considered polluted or impaired. Relevant to how residents of Hinkson Creek watershed value the creek, the majority of the respondents did not hunt or fish, indicating they would not value Hinkson Creek for those purposes.

Process science projects

In addition to the monitoring data collected through Missouri DNR, a suite of studies on hydrology, floodplain processes, and water quality has been developed under the direction of Dr. Jason Hubbart, University of Missouri (presently, West Virginia University). These studies address fundamental processes in the watershed and provide important contextual understanding.

Basin hydrology

Hinkson Creek has been gaged at the USGS site off Providence Road. The gage was installed in 1966 and operated until 1981. The gage was discontinued from October 1, 1981 to mid-September 1986 (fig. 4). It then operated through September 1991 and was discontinued again until March, 2007. The USGS gage was supplemented with additional 4 gages 2008 – 2014 operated by Dr. Hubbart's research program.

The premise of the TMDL listing of Hinkson Creek is that the runoff has increased due to development of the watershed. Although the record of daily mean and mean annual discharges (fig. 4) suggests an increase in runoff over time, runoff needs to be compared to the amount of rainfall in order to assess trends that can be attributed to development. Moreover, understanding of development effects on hydrology should also take into account whether effects are seen as changes in base flow or in direct runoff. A detailed analysis of the daily record at the USGS stream gage indicated that no statistically significant trends were detectable from 1967 to 2010 in annual streamflow metrics (Hubbart and Zell, 2013). It is notable that this lack of trend coincides with a time interval during which population in Columbia increased from 50,000 to 100,000 and developed area increased from 12% of the Hinkson Creek watershed to about 26%. These results do not mean that urbanization has not had an effect on the hydrology of Hinkson Creek; it only establishes that effects are not significant after 1996. A pre-development hydrologic record is not available for reference.

Although the empirical data did not show an urbanization effect, a forward modeling study predicted that runoff and streamflow would increase by significant amounts based on growth scenarios (Sunde and others, 2016). This study coupled a rule-based urban growth model, 3 growth scenarios, and a watershed model (Soil Water Assessment Tool, SWAT). The SWAT model was calibrated on monthly streamflow data from 2007-2010, and validated 2011 – 2014. The three growth scenarios produced increases in streamflow of 12.8 – 19.7% and runoff 14.3-16.8%. The analysis indicates that under likely growth scenarios, runoff into Hinkson Creek is likely to continue to increase, unless actions are taken to mitigate it. The models did not include BMP scenarios which might be implemented to mitigate runoff; such modeling capability would be useful in scaling BMP implementation to quantify a cumulative watershed effect.

A more recent analysis Hinkson watershed hydrology focused on variation in runoff ratios by sub-basin (Kellner and Hubbart, 2016a) and documented that downstream, more-urbanized sub-basins contributed a greater proportion of runoff (compared to rainfall) when compared to upstream agricultural basins. The study also documented linear relations decreasing runoff ratio with increasing agricultural land, as well as increasing runoff ratio with increasing urbanization. The study concluded that vegetation management in the watershed may therefore be indicated as a measure to decrease runoff, but the amount of re-vegetation that would be needed to mitigate urban area effects was not addressed.

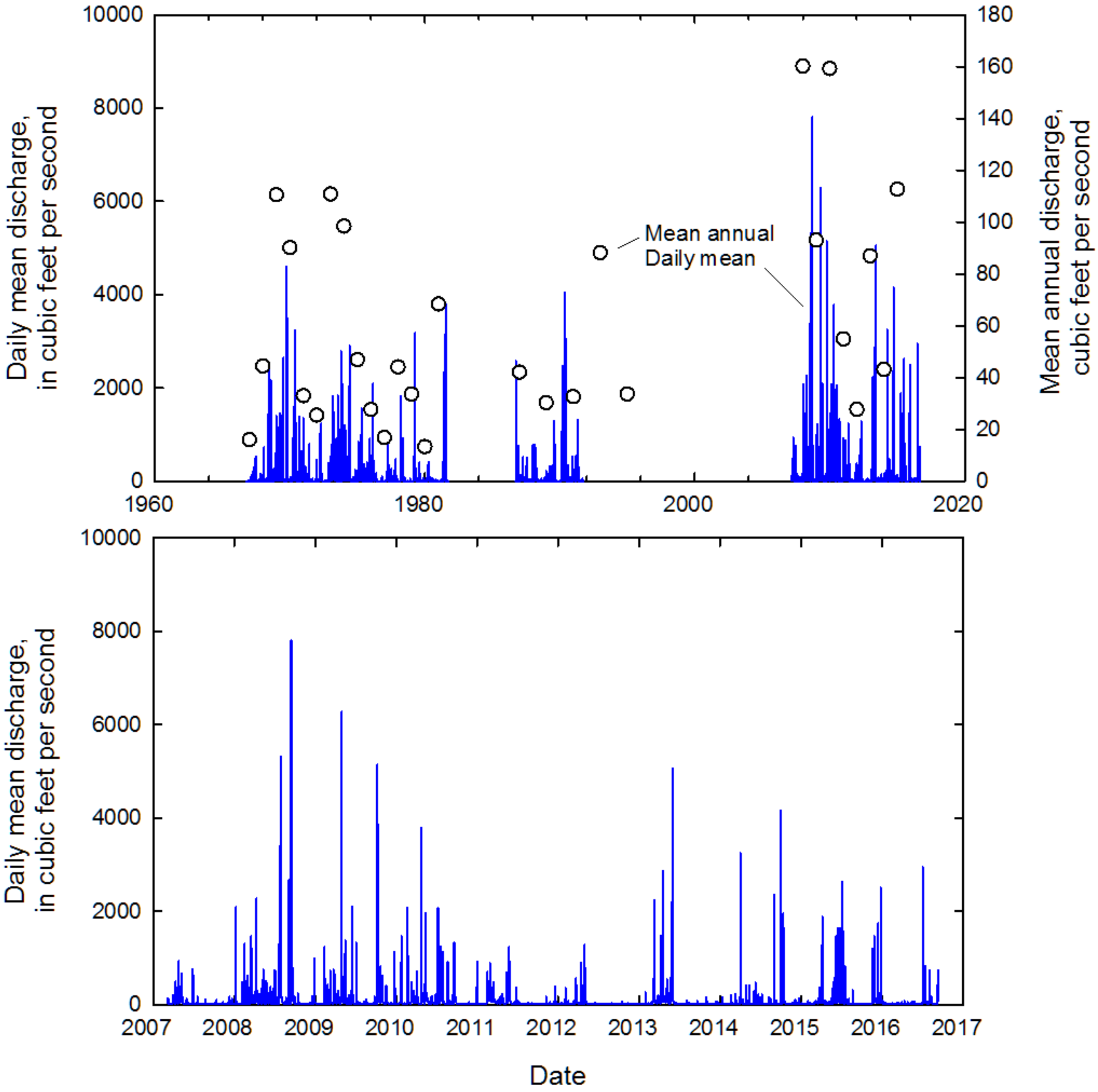

Figure 4. Hydrologic record of Hinkson Creek. Top panel: total record with gaps, daily mean and mean annual discharges. Bottom panel: continuous daily record since 2007.

Sediment

Anecdotal accounts of growth of muddy areas adjacent to the channel (B. Hoppe, pers.. com.) and evident sedimentation in the channel (fig. 5) support the hypothesis that Hinkson Creek has been affected by increased sedimentation in recent years. In the physical habitat assessment, mud was the dominant sediment mapped along the Hinkson Creek mainstem (Hooper, 2015).

Figure 5. Photograph of Hinkson Creek near Twin Lakes, August, 2016.

Studies on sediment in Hinkson Creek include analysis of suspended sediment monitoring data and modeling of suspended sediment concentrations and particle-size distributions (discussed further in following section on future/ongoing science). In addition, a study was conducted on sediment sources, comparing sediment additions from streambank erosion to fluxes in the channel (Huang, 2012). This study attributed significant differences between bank erosion adjacent to bottomland hardwood forest (BHF) and abandoned agricultural land (AG) floodplains to the prevailing land use. The study did not, however, account for other factors, like channel curvature, which varied substantially between the two sites. Although the author concluded that bank erosion adjacent to the AG land use contributed significantly to suspended sediment loads, the calculations were based on one year of data and the sampling design was not spatially randomized, hence generalizing beyond the pilot sites is tenuous. Notably, studies documenting variation in suspended sediment loads in the watershed have implicated increased channel incision and streambank erosion to explain downstream increases in suspended sediment concentrations and loads (Freeman, 2011; Zeiger and Hubbart, 2016a). Together, these data suggest that additional direct studies of bank and bed erosion contributions to sediment load should be pursued.

Studies on particle-size distributions of suspended sediment on Hinkson Creek document intriguing downstream fining wherein particles in the 0.3 – 0.5 mm are common upstream but not downstream (Freeman, 2011; Hubbart and others, 2014b). These authors also found that average sediment particle density apparently decreased in the downstream direction, making it unlikely that fining could be attributed to break up of soil aggregates. An alternative interpretation is that downstream fining and decreasing density could be explained if the proportion of particulate organic matter in the suspended sediment flux increased in the downstream direction. Additional work would be needed to follow up on this hypothesis.

Downstream increases in finer sediment particles (ranging 0.005 – 0.01 mm) might be an indicator of urban influence or it could be a downstream trend that would occur in the absence of urban influence. The nested structure of the sampling stations on Hinkson Creek results in simultaneous increases in urbanization and drainage area moving downstream along the mainstem; hence, it is difficult to separate the two effects in order to implicate one or the other. In addition, it is not clear how the documented changes in particle size distribution of the suspended load would affect biological resources of Hinkson Creek. Additional research would need to be pursued to link the particle-size changes to biological responses.

Subsequent to the Freeman (2011) study, additional analysis of sediment concentrations and loads expanded analysis based on four years of record and using gravimetric rather than laser diffraction data (Zeiger and Hubbart, 2016a). The study confirmed a persistent pattern of decreasing suspended sediment concentrations from upstream agricultural-dominated sites to suburban sites, followed by downstream increases in concentrations in areas with greater urban influence. The authors interpreted the spatial variation to imply that increased runoff in the downstream urban areas is accompanied by increased sediment delivery due to channel incision and bank erosion. Data from one year also indicated that sediment may be stored temporarily in one section of Hinkson Creek; transient storage of sediment is likely to lead to complex flow-sediment concentration relations as sediment load may be transport limited at some times and supply limited at others. This analysis contributes to understanding of suspended sediment dynamics in the Hinkson Creek but does not link sediment dynamics to biological resources.

Floodplain processes

Comparisons between BHF and AG floodplains indicate that the previously cultivated agricultural fields generally have lower mean volumetric water content, lower mean infiltration rates, and slightly higher porosity (Hubbart and others, 2011). The increase in mean porosity from AG to BHF – reflecting the maximum water holding capacity – was 1%. In a subsequent study with instrumented volumetric water content (VMC) measurements, VMC increased from 32.8% to 33.1% from AG to BHF (Kellner and Hubbart, 2016b), a small but statistically significant difference. One of the pervasive differences noted between AG and BHF was the much greater spatial variability under BHF, presumably reflecting secondary porosity distributions associated with tree roots. One modeling study estimated 28% greater storage in the vadose zone in the BHF compared to AG, confirming measurements that indicate greater infiltration and water-holding capacity in floodplains underlying BHF; increased storage under BHF was attributed to greater evapotranspiration and effects of macropores (Zell and others, 2015). Additional studies documented differences in spatial variability of VMC that were attributed to differences in land-use practices, specifically that the history of cultivation in the AG site had spatially homogenized soil characteristics compared to woodland; other components of spatial variation, especially at depths greater than cultivation or rooting, were attributed to geologic difference at the sites (Kellner and Hubbart, 2016b). Another analysis of groundwater flow data (Kellner and Hubbart, 2016c) concluded that horizontal groundwater flow was substantially more variable at the BHF site compared to the AG site, and somewhat higher.

The body of information developed on the BHF and AG sites on Hinkson Creek establishes the potential for BHF sites to have statistically different hydrologic rates compared to AG sites; furthermore, most of the rates established are positive from the perspective that they would tend to increase floodplain water storage. Turning this information into decision relevant information requires scaling up from the site-specific studies to assess overall effects on Hinkson Creek. Although BHF land use has been shown to have positive hydrologic effects, it is not clear that implementation of BHF riparian land use could take place at a scale sufficient to have substantive hydrologic effect. To be substantive, the modest increases in water-holding capacity and infiltration rates in BHF dominated floodplains (a maximum of 6% of the watershed) would need to compensate for the increased runoff associated with impervious area and other land uses in 94% of the watershed. The scaling question is generic to the application of science to decision making on Hinkson Creek. In the case of floodplain functions, the scaling analysis would need to address floodplain storage relative to flood volumes, floodplain volume available for storage along the creek, and floodplain infiltration rates relative to flood longevity. With horizontal groundwater flow rates on the order of 0.01 m/day (Kellner and Hubbart, 2016c), flow rate is likely to limit infiltration to an extremely small percentage of a bankfull flood volume.

Water Quality and Nutrients

Data on Hinkson Creek water chemistry have been collected in conjunction with the DNR bioassessment sampling. The data include *in situ* measurements of discharge, temperature, conductivity, dissolved oxygen, and pH. Additionally, surface water grab samples are submitted for laboratory analysis of turbidity, ammonia, nitrate+nitrite, total nitrogen, total phosphorus, sulfate, non-filterable residue, calcium, magnesium, and total hardness. The sampling protocol is intended to provide contextual covariates for the spring and fall bioassessment samples rather than a long-term or comprehensive monitoring of water quality.

Additional data on chloride were collected in a USGS study (Allert and others, 2012); this project was intended mainly to explore sensitivity of aquatic organisms to peak chloride concentrations in Hinkson Creek during a winter snowmelt event. Chloride in two of the samples substantially exceeded EPA standard (1250-4300 mg/l compared to

230 mg/l standard). Toxicity tests with *Ceriodaphnia dubia* documented significant effects on survival and reproduction with prevailing chloride concentrations. This study, too, was not intended as a long-term monitoring program, but did establish a possible link between water chemistry and impairment of stream biota. An extended analysis of chloride concentrations and loads in Hinkson Creek documented increasing chloride concentrations from upstream to downstream as sources of chloride (assumed to be road salt) increased (Hubbart and others, 2017). Modest decreases in concentrations at downstream stations 4 and 5 were attributed to a greater proportional increase in runoff that served to dilute concentrations. Chloride concentrations rose above chronic and acute EPA levels for substantive time intervals 2009 – 2014, with highest concentrations in the late-winter and spring. Persistent chloride concentrations (below chronic exposure levels) in summer were explained as releases from storage in alluvial aquifers. These two studies, together with the invertebrate results of Nichols and others (2016), document potential for chloride to affect Hinkson Creek invertebrate communities. Improved understanding of the role of chloride would need to be developed through exposure studies with typical Hinkson Creek invertebrate assemblages. As noted in Hubbart and other (2017) mitigation for chloride may be problematic because of the value of road salt applications in public safety. This same factor would complicate field-based adaptive management experiments with reduced chloride because substantive areas of the watershed would have to forego road-salt treatment.

The effects of urbanization on stream temperatures were explored with the nested gage design (Zeiger and Hubbart, 2015). The authors found that daily mean water temperatures data at the upstream, agriculturally dominated site had consistently lower water temperatures by 0.2 – 0.7 ^{o}C (Zeiger and others, 2016) compared to the more urbanized downstream sites. Increases in temperature in the downstream sites was interpreted as the effect of runoff from heated, impervious surfaces that were more common in downstream areas (Hubbart and others, 2014a; Zeiger and Hubbart, 2015). During a three year period, site 3 in the middle of the stream section had 55 days when water temperatures exceeded 32^{o}C. Water temperatures were also correlated with canopy opening over the creek, indicating that riparian management could affect stream temperatures. Summer storms had a substantive effect on stream temperatures, raising mean water temperature by 2.7^{o}C and lasting an average of 5.1 hours; temperature surge magnitude and duration were positively correlated with percent urban land use and negatively correlated with width of the riparian buffer. The authors also explored modeling of runoff and surface water temperatures with SWAT (Zeiger and others, 2016). This work documented that SWAT tends to underestimate peak discharges but that water temperature modeling, using various algorithms, can be modeled with useful accuracy.

Assessment of nutrient concentrations and fluxes at nested mainstem gages documented spatial variability related in expected and unexpected ways to land-use patterns (Zeiger and Hubbart, 2016b). Over four years of monitoring, average total nitrogen and total phosphorous concentrations are highest in upstream agricultural areas and decrease downstream with increasing drainage area and suburban influence. Further downstream, as drainage area and urban influence increase, both total nitrogen and total phosphorous increase somewhat, leading to speculation that sources of nutrients and sources of water interact in ways that provide a mid-basin zone of relatively low nutrient effect. Increased nutrient loading in the urban areas of Hinkson Creek may result from lawn fertilization. Temporal and spatial patterns can also be interpreted to indicate seasonal and multi-year lags, possibly indicating transient storage of nutrients (possibly bound to sediment) and later release. Inorganic nitrogen concentrations did not exceed federal or state water quality standards during the study; maximum total phosphorous concentrations frequently exceeded EPA recommended concentrations. Elevated nutrient concentrations in Hinkson Creek could lead to increased primary productivity, algae blooms, high biochemical dissolved oxygen demand, and shifts in the invertebrate communities toward scrapers.

Exploration of modeling of Hinkson Creek nutrient and sediment dynamics, calibrated and validated against the datasets described above (Zeiger and Hubbart, 2016c), indicated some promise, but also multiple areas of improvement that are needed to accurately model nitrogen, phosphorous, and sediment fluxes. Difficulties in modeling extreme events and instream nutrient processing were apparent. Additional model complexity may be necessary to provide useful modeling tools for managing nutrients and sediment.

Study of groundwater chemistry at the BHF and AG sites discussed above also showed significant differences in nutrients and trace elements (Kellner and others, 2015). Although the authors deferred many interpretations to further study, they attributed much of the change to the land-use history. As indicated by the authors, the specific hydrology of the sites probably plays a role and it is worth noting that the AG site has a large managed wetland adjacent on the same valley bottom, and the BHF site is fed by a local tributary that drains the MU golf course; clearly, these local hydrologic influences may be affecting groundwater chemistry.

Biological Structure and Process

Whereas the DNR bioassessment monitoring and resultant MSCI metrics provide the foundation for assessing regulatory status and trends for Hinkson Creek, additional studies have addressed information needed to understand cause and effect. An assessment associated with the 5 gaging sites evaluated systematic effects of land use, instream habitat quality, and water quality on macroinvertebrate assemblages during 2011, based on taxonomic and trait metrics (Nichols and others, 2016). This study confirmed that the agriculture-urban gradient is reflected in many macroinvertebrate trends, including upstream to downstream decrease in sensitive species (Ephemeroptera, Plecoptera, and Tricoptera, EPT). Habitat variables showed similar trends, notably a fining of substrate in riffles and decline in root mat volume from upstream to downstream. Community richness and diversity were not significantly different between dominantly agricultural sites and those that had more than 10% urban area, a surprising result that was interpreted as evidence that even the agriculturally dominated sites in Hinkson Creek have been significantly affected by disturbance. Many of the relations explored among habitat variables, land-use, and invertebrate metrics varied by season and by position in the stream network, indicating the potentially complex relations among assemblages and stressors. The most significant trend related to urbanization was the decrease in small-bodied invertebrates in urban areas.

Nichols and others (2016) also documented relative high chloride concentrations. Similar to Allert and others (2012), they found concentrations were higher in urban areas and exceeded EPA chronic limits in some cases. Because the respiration traits and body sizes of invertebrates sampled did not correlate with dissolved oxygen (DO), it was concluded that DO is probably not limiting for assemblages. Presence of multi-life-stage organisms in downstream riffles correlated with peak flows, which was interpreted as evidence that disturbance may be a factor structuring those assemblages. Burrowing organisms were more abundant in downstream reaches that also had more fine sediment, indicating that fine sediment deposition can be a factor in structuring assemblages. A downstream decrease in rheophilic invertebrates was correlated with downstream decrease in root mat volume, indicating that factors determining occurrence and persistence of root mats, such as occurrence of large, scouring floods, may be important to assemblages.

Projects to mitigate impairment of Hinkson Creek, completed and in progress

Multiple projects intended to mitigate impairment of Hinkson Creek have been completed to date, and other projects are planned or in progress. Project designs have been guided by the general objective of diminishing point and non-point sources of potential pollutants, and decreasing runoff. Although all the projects make use of best management practices and clearly contribute to improving runoff condition for Hinkson Creek, designs have been handicapped by a lack of understanding of the specific processes which have led to impairment. Without this understanding, it is not clear whether the efforts demonstrate the optimal use of resources.

Categories of projects

Since Hinkson Creek was listed in 1998 a large number of projects have been completed. The projects fall into 7 broad categories:

- Elimination of substandard private sewage treatment systems (both private common collection elimination and publically owned systems). These projects have undoubtedly contributed to decreases in nutrient and bacterial loads to Hinkson Creek.
- Elimination of specific presumed sources of contamination. Relocation of the Missouri Department of Transportation salt storage facility is a specific project that presumably decreased direct chloride loading to Hinkson Creek.
- Projects to intercept, spread runoff for infiltration (level spreaders). These projects are designed to intercept runoff from channelized flow and spread it out over low-gradient surfaces (swales or floodplains) where it can infiltrate into groundwater. One of these projects has been completed and is being evaluated. The cumulative effect of existing and planned level spreaders is unknown.
- Large retention or detention systems[1] (basins, ponds, and lakes, construction or retrofits). A variety of

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[1] Retention basins are ponds or lakes that are intended to have water in them most of the time. Depending on specifics of construction they may have some limited flood storage capability. Because they have water in them, they provide water quality benefits by allowing for sediment and nutrient sequestration and processing. Detention basins are usually dry and operate to detain runoff peak flows and drain slowly after storm events. Retrofits of

lakes and ponds exists in Columbia and county areas in the watershed. Some have been designed as detention basins although most were designed for retention or other aesthetic or recreational value. Although these basins are presumed to have beneficial effects in decreasing peak flows and increasing water quality, the cumulative benefits are not quantified.

- Small, widely distributed retention/detention projects (rain gardens, rain barrels, bioswales, and pervious pavement). These projects are located throughout Columbia, MU campus, and suburban county areas. They should contribute to decreasing runoff and increasing water quality, but their cumulative effect is unknown.
- Land stabilization (uplands, streambanks). Most of these projects are streambank stabilization projects designed to protect infrastructure but with other potential benefits in decreasing sediment and nutrient loading to streams. Net benefits of streambank stabilization are difficult to quantify because stabilization of one section of stream often transfers erosive energy to the next bend downstream. Moreover, streambank stabilization disrupts natural ecological processes of delivery of large woody debris to the stream and rejuvenation of floodplain habitats associated with channel migration. As noted above, streambanks probably contribute substantial sediment to streams, but the amounts, and therefore the benefits of stabilization, are poorly quantified. Upland stabilization of disturbed areas through erosion controls and revegetation acts to decrease sediment delivery to the stream.
- Riparian buffers (purchase, easement, planting). These projects are intended to provide stream shading (to decrease water temperatures), bank stabilization, interception of some runoff, and enhanced infiltration into floodplains. Extensive research has been completed on floodplain processes on Hinkson Creek (discussed above). Opportunities for establishment of woody riparian buffers is limited in the city because most riparian areas already have woody vegetation corridors; greater opportunities exist upstream in the county (Hooper, 2015).

Monitoring, assessment, and evaluation of projects

Under adaptive management, projects are informed by and designed with the best available science (*design, implement stages* of the adaptive management cycle, fig. 1). *Monitoring* and *evaluation* of projects are intended to provide additional scientific information to reduce uncertainties and provide for improved designs and decisions (*adjust* stage). Assuming that the problem has been adequately assessed, learning from projects includes three fundamental questions. These three questions are discussed here with respect to a generic level spreader project:

1. **Does the project work as designed?** This is an engineering question, and focuses on whether the project meets design specifications. The objectives and design of a project are presumably based on best available scientific information indicating that the project will contribute to mitigation of stream impairment. In the case of a level spreader project, design specifications may be related to how much water is diverted into the infiltration field, when this occurs, how much peak flow from the contributing drainage area is decreased, or how much change in water quality occurred.

2. **Does the project measurably mitigate impairments to Hinkson Creek?** This is a more complex and challenging question, in large part because the cause(s) for impairment are not yet known. In terms of chemical impairment, one can ask whether a level spreader mitigates run off of lawn and garden chemicals or other urban contaminants that could be an impairment to invertebrate populations. On the physical side one can ask whether a level spreader will store floodwaters, decrease peak flows downstream, decrease sediment yield to the creek, or decrease bed disturbance that could be impairments to stream biota. These questions are all preconditioned on knowing what the likely impairments are.

    - Every project has the potential to increase relevant learning about Hinkson Creek, but when the causes for impairment are unknown, the project learning objectives are likely to be unfocused as well. Lack of focus in learning objectives is likely to lead to assessments that are overly broad and ineffective in providing decision-relevant information.

3. **How does the level of effort in the project scale up to make a difference in Hinkson Creek?** This question would logically come after answers to the first and second, because it assumes that impairment is understood and effect of the project on the impairment is measurable. This question differs from the others,

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detention basins may be used to increase permanent pools to increase water quality benefits. Retrofits to retention basins serve to change the characteristics of the drainage system and spillway to add flood storage.

however, in additionally addressing the question of *how much is needed*. How much does a level spreader affect Hinkson Creek, and how many more similar projects would need to be implemented to have a positive, mitigating effect on impairments to the creek? The Science Team refers to this type of question as a "scalability" question.

- Understanding how project implementation would scale almost always requires the ability to use computer-based simulations similar to the SWAT modeling efforts discussed above. Models need to be reliable enough to accurately quantify effects of projects. Scalability is highly relevant to decisions because it addresses the scope of future investment needed to mitigate impairment. How much is needed and how much can be done given practical constraints? Is this a practical solution?

Questions 2 and 3 should not necessarily be addressed sequentially. They are both critical to the success of a project and should be, in most cases, addressed simultaneously.

Recently, a plan for improving the condition of the riparian corridors was approved. The riparian corridor project shares the same assessment questions discussed above. Will it perform as designed? Will it mitigate causes of impairment? How much will it affect the creek -- is it enough to make a difference? Clearly, the answers to all these questions are preconditioned on knowing (or hypothesizing) the cause for impairment and having an objective to mitigate that cause. While there are many potential ecological benefits of increased riparian corridor, there is also risk that it will not mitigate the actual causes of impairment if those causes are undefined. Moreover, the lack of focused project objectives results in a very wide range of responses that could be assessed for project performance. The wide range of responses dilutes the investment in monitoring and assessment among many potential response variables instead of focusing on the responses that are relevant to impairment and that would provide the highest information value. Scalability of the riparian corridor project is key: how much riparian corridor is available to be managed and is it enough to make a difference? If the impairment is related to elevated water temperature, the riparian corridor may act to shade and lower temperatures considerably. On the other hand, if the impairment is related to peak flood flows, it is unlikely that enough riparian corridor with enough groundwater storage is available to mediate flood peaks.

Decisions on whether to act or learn are generic to adaptive management under conditions of pervasive uncertainty. The tradeoff is between early investment in science and learning compared to early investment in management projects. The former risks a lack of progress in doing on-the-ground projects while information and learning is prioritized. The latter risks construction of projects with insufficient information to guide the objectives, especially if the problem has not been adequately assessed. The preferred balance is a question of the level of risk that stakeholders are willing to tolerate.

Decision-relevant science priorities

Scientific understanding of Hinkson Creek has grown tremendously since 2012. Important information on the structure of Hinkson Creek, the physical habitat context, and process-level understanding of runoff, sediment transport, floodplain hydrologic processes, macroinvertebrate communities, and nutrient fluxes now exists that did not before. At the 5-year mark it is appropriate to assess what is known, what is not known, and what needs to be known to mitigate the impairment(s) of Hinkson Creek. The science pursued to date has been mostly within the "*Assess problem*" stage (fig. 1). The science priorities described below continue in the problem assessment stage because causes(s) for impairment have yet to be identified with confidence. The priorities outlined, however, rely on the solid foundation of science that now exists, to focus specifically on identifying causes. Diagnosing the impairment(s) continues to be the fundamental challenge.

The following section presents the Science Team's consensus on high-priority science topics. The discussion is presented in terms of hypotheses that relate to the Hinkson Creek CEM (fig. 3), with emphasis on the physical and chemical sides of the CEM. These projects have been selected because of their perceived high benefit: cost ratio; results of a survey of indices of benefits, costs, and benefit: cost ratios are shown in table 3.

Macroinvertebrate Community

The focus of the CAM process is on the stream macroinvertebrate community and its contribution to the MSCI score. The characteristics of that community are therefore foundational to prioritization of science, especially if the community can provide diagnostic indicators of the source(s) of impairment.

Studies on the stream macroinvertebrate community

These studies address the base of the CEM, reasoning from characteristics of the macroinvertebrate community upward to determine the likely source(s) of impairment. The macroinvertebrate community studies are important to Hinkson Creek management and restoration decisions because they start with the direct evidence of impairment. Basing prioritization of future science efforts on what is learned from the macroinvertebrate community should focus learning on those processes that are most relevant to identifying impairment of the creek.

1. **Additional analysis of existing macroinvertebrate data.** Separating physical and chemical influences on the macroinvertebrate community is complicated by the interaction of chemical factors and physical factors: it is difficult, for example, to separate the effect of riffle quality from water quality to explain metrics like the MSCI. On the other hand, analysis of traits and tolerances may help explain why community samples are dominated by specific taxa. Some of the spatial relations noted by Nichols and others (2016) suggest that additional analysis of existing data, especially with the context of the field-based physical habitat assessment, may provide insights into causes for community shifts and impairment. Because the DNR sampling protocol specifically examines species with differing levels of tolerance for some pollutants (for example, PAHs, metals) additional analysis of data from the 11 sites may be able to differentiate effects of specific chemical stressors. This project would have relatively low cost and potentially large benefit in narrowing focus to particular stressors and/or particular parts of the creek. A thorough analysis would include assemblages in reference streams and in museum collections.

2. **Colonization experiment on uniform substrate**. An approach to separating chemical stressors from physical habitat stressors is to provide uniform habitat along the creek using rock baskets. This serves to eliminate the physical habitat effects so the invertebrate community colonizing the baskets should be affected almost completely by water-column chemistry. The approach would be to place rock baskets in common hydraulic environments in 20 or more locations along the stream during a period of time in the summer. Replicates of the experiment during different seasons could address seasonal issues like chloride or PAH loading. The locations would be informed by the physical habitat assessment, water quality variability, and location of tributaries and storm water inputs. Water-quality covariates would be measured periodically during the experiment with emphasis on indicators such as DO, conductivity, and temperature. If there is little or no difference among invertebrate communities that have colonized the substrates, one would conclude that water chemistry is not a major stressor and attention would turn to physical habitat. On the other hand, if communities did vary, water quality would be implicated as a source of impairment. Covariate water quality samples may prove useful in interpreting the cause of impairment, or the results may point toward the need for more detailed water-quality assessments. The project would have moderate cost and potentially large benefit in defining the type, and possibly location, of stressors.

Physical_Habitat

Projects currently underway

Two projects related to Hinkson Creek physical processes are currently underway under Dr. Hubbart’s direction at the West Virginia University. The first is “Hinkson Creek: Quantifying Stream Flow and Suspended Sediment Response to Urbanization” and is an extension on the work already reported in Zieger and Hubbart (2016a, c). The objectives are to estimate interactions of land use on stream hydrologic responses and sediment transport. The approach is to use the extensive existing dataset to calibrate hydrologic models, improving on existing modeling (Zeiger and Hubbart, 2016c), and using the model to assess sensitivity of Hinkson Creek to past and future land-use changes.

The second effort addresses environmental flows in Hinkson Creek; however the proposal and description are not available. From the context, we assume that the study will use the hydrologic record developed on Hinkson Creek to calculate metrics related to ecological responses, similar to the Index of Hydrologic Alteration (IHA) or similar derivatives (Richter and others, 1996; Henriksen and others, 2006; Kennen and others, 2009).

Future projects

Conditions and processes that affect the macroinvertebrate community fall into two main categories: chemical and pathogen exposure or physical habitats (fig. 3). Although the pathways that lead to these two categories share a common thread of runoff as the transporting agent, the origins and potential mitigations are very different. Toxin and pathogen exposures originate from processes – for example road salt applications, PAH runoff from parking lots, leaking sewers – that would be effectively mitigated by specific management actions. Physical habitat degradation or disturbance, such as bed sedimentation, or bed scour, originate from different processes, typically acting on different parts of the landscape and therefore having different solutions. Excessive sedimentation, for example, tends to be associated with delivery of sediment from disturbed land, gullies, or bank erosion. Although there may be multiple sources of stress on the macroinvertebrate community, determining whether stresses are dominated by the chemical pathway, the physical pathway, or both would help narrow the field for more effective learning and management.

Assessment of sedimentation, channel dynamics, and invertebrate habitats

Studies that document source, transport, and fate of sediment in Hinkson Creek will provide powerful inference about linkages from sediment to stream biota. In general, scientists are confident in their knowledge that sedimentation that overwhelms a stream, filling pools and clogging interstices of available riffle habitats is injurious to the benthic ecosystem and will result in degraded insect and fish communities. On the other hand, if the stream is not overwhelmed, benthic communities may shift in subtle ways that would require additional study to define the cause for impairment.

If sediment is determined to be a significant impairment to the macroinvertebrate community in Hinkson Creek, additional work may or may not be needed to determine the source and solution. This will depend on the magnitude of the problem documented and the spatial distribution. If areas of Hinkson Creek are discovered that are overwhelmed with sediment, where those areas exist may give sufficient insight into the upstream origins. It is possible, maybe likely, that the spatial distribution will not provide that information, and additional work will be needed to assess where the sediment is coming from. In many cases, sediment sources can be classified into streambank erosion, gullies associated with intensive land disturbance, and broadly distributed non-point sources from agricultural lands. As discussed above, once the impairment and the source are understood, mitigation processes would need to be designed to address whether the mitigation is effective and can be scaled to make a difference.

One of the dominant hypotheses for impairment is excessive deposition of fine sediments that thereby degrades habitat for benthic macroinvertebrates. A common result of deposition is to shift the invertebrate community away from EPT taxa to more tolerant taxa such as tubificid worms. Although suspended sediment fluxes at the 5 gages can indicate sources and possibly sinks of sediment, assessment of deposition is necessary to document that the sediment is actually impairing the benthos. We recommend four relatively simple and low-cost approaches to developing understanding of bed deposition.

3. **Intensive longitudinal mapping of fine sediment**. This project is an enhancement to the field-based physical habitat assessment and is underway (as of May 2018). The approach is to assess thickness of fine sediment at closely spaced locations in the thalweg of the mainstem of Hinkson Creek. The method is to use a metal rod that can be inserted into the bed for measuring the depth of refusal. The intent is to evaluate spatial variation in the thickness of deposited sediment with other physical habitat assessment data to infer the origins of sediment in the channel. The data should also serve to confirm which parts of the Hinkson Creek channel are affected by backwater from the Missouri River, and therefore might be considered as a separate process domain. This is a low-cost project with potentially very high benefits in documenting where sedimentation is acute in the creek. The locations of acute sedimentation may be indicative of sources.

4. **Transect based surveys of bed sedimentation and erosion.** In addition to the spatial distribution of acute sedimentation and possible inference of sediment sources, variation in sedimentation over time is of interest, especially if sedimentation is increasing or decreasing in severity, or moving downstream. Temporal sedimentation is best documented through resurveys of channel transects. Transects would be located through a randomized design, perhaps stratified by creek segment. Randomization will allow for unbiased interpolations of results. Transects would be surveyed at least annually and after major sediment-transporting flows; variation through time will indicate whether sedimentation is moving downstream, and if so, at what rates. The cost of transect resurveys is moderate if carried out by students and the benefits in terms of understanding whether sedimentation is accelerating or decelerating would be large. The decision to invest in this project would logically

wait until invertebrate distribution data indicated that sedimentation is a likely cause of impairment.

- The same transect approach could be used for a corollary hypothesis: invertebrate communities are impaired by bed scour and disturbance. This hypothesis typically applies to coarse sediment remobilization and may occur with or without excess delivery of coarse bedload sediment. That is, it could be linked to increased peak flows capable of transporting coarse sediment, with or without increased sediment loading. Transect resurveys will indicate the extent to which bed disturbance by scour -- especially in riffles – is likely to affect invertebrate communities.

5. **Photo documentation of Hinkson Creek changes through time**. This project has elements of both scientific documentation and outreach. The project would create a website and would solicit photographs of Hinkson Creek from Boone County citizens. Historical photographs would provide useful context for understanding the nature of change in Hinkson Creek, including whether bed material, large woody debris, or bank conditions have changed significantly. Historical photos for which the location can be verified can be replicated to document changes. The website would provide opportunities for citizens to be part of the Hinkson Creek management effort through citizen science and would provide documentation of how much or how little Hinkson Creek has really changed. An example of a similar project has been completed by the University of Vermont (http://www.uvm.edu/landscape/). This would be a project with moderate cost because of the staffing needed to curate the collection and keep the website up to date; the benefits could be substantial, both in documentation of change and in outreach.

6. **Evaluation of Missouri River backwater effects**. This question addresses the extent to which backwater flooding from the Missouri River influences the lower parts of Hinkson Creek. This question has been assessed (but not published) using data from both Missouri River and Hinkson Creek hydraulic models and Hinkson Creek LiDAR. Having delineated the zone of backwater effects, the effect on macroinvertebrate communities can be addressed in more detail through 1) evaluating how existing physical habitat variables change in this reach and 2) evaluate how invertebrate communities and MSCI metrics vary upstream and downstream of the zone of influence. The results of these studies may indicate that upstream and downstream parts of the creek are affected by substantially different sediment-transport processes, some of which may be amenable to mitigation (upland sediment yield) and some of which (backwater effects) will not be. These analyses can be initiated with existing data from the physical habitat assessment and DNR invertebrate data (site 1 is in the backwater zone and site 2 is just upstream). The cost for initial analysis is very low and the benefits may be quite high if they lead to reclassifying the impaired reach of Hinkson Creek; however, discussions with Missouri DNR indicate that reclassification could be impractical given time and data requirements.

Evaluation of bank erosion as contributor to sediment delivery

The hypothesis that excess sediment is being delivered to Hinkson Creek carries with it the fundamental question about the source of the sediment. Many reviews of sediment loading in the literature confirm the conclusions of recent work on Hinkson Creek (Huang, 2012) that bank erosion is a potentially significant source of sediment delivery to stream. We recommend a two-phase approach to address this question and to scale up from the spatially limited results of Huang (2012).

7. **LiDAR measurement of bank retreat and sediment delivery.** A cost-effective first phase would be to use the 2015 and 2009 county LiDAR datasets to automatically map bank retreat. The phase 1 GIS-based physical habitat assessment developed tools to process LiDAR to automatically delineate the top of the bank. This method, with or without some level of manual intervention, would provide 2015 bank lines that can be compared with the 2009 bank lines to quantify bank retreat in the intervening 6 years. With bank heights measured by the field based physical habitat assessment, locations and quantities of bank erosion can be calculated with a high degree of accuracy. The analysis would either confirm or contradict the hypothesis that bank erosion is contributing significantly to sediment delivery to the creek. The project might be postponed until sedimentation has been confirmed as a stressor on macroinvertebrate communities. Because this analysis is based on analysis of existing data it would be relatively inexpensive while providing fundamental information on Hinkson Creek channel dynamics.

8. **Transect based resurveys of bank erosion.** If the first phase confirms a substantive role for bank erosion, the next phase would be to put in place more detailed transect-based surveys to refine quantities of sediment delivery and improve documentation of events that contribute to bank erosion. The optimal approach to providing unbiased estimates for the magnitude of bank erosion would require randomized erosion transects throughout the Hinkson Creek mainstem. Resurveys of transects would quantify magnitude, location, and timing of bank erosion, and it is possible that a common set of survey transects could be used for assessment of bank erosion and channel deposition and scour. To capture segment- and reach-scale variability along the creek would require a large number of transects, potentially numbering several hundred. Annual or event-based resurveys would be time consuming, requiring a crew of at least two and several hours of field time per transect. The benefit of the data, however, would be substantial because it would refine estimates of sediment loading from bank erosion and indicate where and how often it occurs, pursuant to identifying sedimentation as a significant stressor. The number of transects could possibly be minimized by stratifying by erosion intensity classes identified in the first phase before randomizing.

Identification of intensively eroding banks may lead to prioritization of sites for bank stabilization. Caution is warranted, however, in implementing bank stabilization as a measure to mitigate sediment delivery, because bank stabilization often results in transfer of energy to downstream unprotected banks, moving the problem without solving it and perhaps amplifying the problem (Fonstad and Marcus, 2003). Moreover, bank erosion is a fundamental ecological process in streams providing a disturbance mechanism, delivery of large woody debris to the channel, and opportunities for deposition of new surfaces for colonization of woody seedlings (Johnson, 2000; Trush and others, 2000; Florsheim and others, 2008). Stakeholders may want to compare these potential ecological benefits with benefits of bank stabilization.

Chemical Pollutants

Chemicals may not only kill individuals, but can act as a disturbance or reduce the ability of species to reproduce through a number of mechanisms. Chloride has been shown in a number of studies to impact aquatic species and the removal of the MoDOT salt storage facility is likely to have increased water quality downstream of that point. However, many chemicals have multiple sources with the watershed and it is possible that a complex combination of chemicals is impairing the stream ecosystem. The original Phase I-III DNR stream surveys employed toxicity testing and indicated some concerns about PAH’s, petroleum products, pesticides, metals, and chloride, but apparently not at a level consistent with listing these chemicals as a cause of impairment. The left hand side of the CEM (fig. 2) depicts the pathways for chemical contaminants to affect macroinvertebrate communities. Importantly, sediment and flow regimes are shown to interact with biogeochemical regimes, indicating the interdependencies among these processes. The following studies are discussed in terms of their benefits and relative costs in addressing chemical pollutant stressors.

Expanded water quality monitoring

An expanded water-quality monitoring network would provide useful information about how common water-quality variables – DO, conductivity, temperature, pH – vary over time and space. Analysis of such data would provide insights into origins of water-quality stressors by correlating where and when anomalies occur with potential sources. Because of the cost of deployment, we recommend that targeted water quality monitoring follows after analysis of invertebrate or colonization experiment data because those results would narrow and focus monitoring to specific places and times.

9. **Increased chemical sampling of major constituents**. Sampling of major constituents (chloride, dissolved oxygen, phosphorus), in addition to pH and temperature, would help to refine understanding of possible chemical stressors in Hinkson Creek. Water data have been collected by DNR and through the work of Dr. Hubbart and his students, but those datasets do not have the spatial and temporal coverage needed to assess where and when there would be effects on Hinkson Creek and its biological community. Increased water quality sampling should try to capture daily variation in constituents with as many as 12 sites along the creek. Although water quality sampling can be expensive, this level of detailed information is needed to narrow down potential chemical stressors. After an initial deployment of water quality stations, the network may be reduced in scope to concentrate on emerging problem areas.

10. **Aquatic organism exposure studies**. After understanding of impairment to the macroinvertebrate community is refined through field studies and chemicals of concern are identified, the importance of those chemicals in stressing the insect community can be addressed in targeted exposure studies. Exposure studies would determine if the magnitude of the effect of chemical pollution is likely to have an effect on the specific macroinvertebrate community of Hinkson Creek (in contrast to conventional test organisms). One type of study would be an in-situ sampling of benthic insect communities using artificial substrates. Use of artificial substrates removes the interaction of the community with available habitat and will serve to isolate water-column chemistry effects on the communities. Another type of study is putting caged test subjects into the creek to assess mortality and chemical uptake, or under controlled laboratory conditions to test effects of specific chemicals or mixtures. Exposure studies can be moderately expensive, but have the benefit of making the clear connection to impairment of biota.

Additional study ideas

In the process of surveying the Science Team for study priorities, additional study ideas emerged. The sequence of ideas is not indicative of priority.

11. **Evaluation of Hinkson Creek fish community responses to stressors**. This study would be a longitudinal assessment of the Hinkson Creek fish community. The objective would be to refine cause/effect understanding of impairment(s) by associating fish community composition with stressors along the stream. The study would involve longitudinal sampling of the fish community including seasonal sampling, replicated over years to explore relations between valley-scale and watershed-origin stressors and fish communities. The study would provide additional diagnostic understanding of stressors in Hinkson Creek. It would be complex but could be a graduate student project with proper technical oversight.

12. **Evaluation of invertebrate community responses in streams affected by Missouri River backwater**. This study would compare invertebrate communities and habitats in the backwater-affected parts of Hinkson Creek with those of other Missouri River affected stream communities. The objective would be to develop a rationale for segmentation of Hinkson Creek and definition of improved reference streams. The study would involve a hydrologic and geomorphic analysis to identify backwater-affected parts of Missouri River tributaries and coordinated sampling to determine whether there are affinities among the invertebrate communities of identified streams. This is likely a complex and multi-year project.

13. **Integrative watershed modeling to assess cumulative effects.** This study would develop, calibrate, and deploy a watershed model to evaluate the cumulative effects of implementation of best-management practices (BMPs). The objective would be to develop a framework to evaluate cumulative effects of BMPs as they scale up throughout the watershed. How much area, how many projects would be needed to have a measurable effect on physical and chemical processes in Hinkson Creek? The modeling framework will be used to evaluate the level of implementation needed to have an effect on the mainstem as well as to determine optimum placement of BMPs. Success will require a well-calibrated model that can accurately predict present-day flows, sediment transport, and chemical fluxes, combined with accurate representations of how BMPs will alter conditions. This is an ambitious project especially as some BMPs will be challenging to model.

14. **The role of physical habitat disturbance in Hinkson Creek.** This study is an analysis of existing data to evaluate disturbance potential of mainstem Hinkson channel segments. The objective is to determine relative disturbance potential of parts of Hinkson Creek by calculating stream power (a measure of stream energy based on the product of depth and slope). Ability to calculate water-surface slopes is afforded by existing HEC-RAS modeling results recently provided to the Science Team. Assessment of the longitudinal variability in stream power may provide insights into potential for habitat disturbance, sediment transport, and habitat disturbance along the mainstem. Data needed to make these calculations are readily available so level of effort is limited to data analysis and reporting. The information would be highly complementary to the physical habitat assessment.

Socio-economic investigations into Hinkson Creek values

The Science Team did not prioritize socio-economic investigations, but recognized that a survey of stakeholders' values and interests may be useful to long-term management planning. Listing of Hinkson Creek on the 303(d) list as an impaired waterbody is an articulation, through the regulatory process, of societal values supporting safe, fishable and swimmable water. Possibly, the residents of Columbia and Boone County would value additional characteristics, and would be willing to pay for management actions that would support them. For example, Hinkson Creek could be fishable and swimmable but still be subject to household trash accumulations and therefore suffer diminished aesthetic appeal. Residents might be unaware of the potential that Hinkson Creek has to offer for recreational and aesthetic benefits. Provision of additional benefits could have implications for real estate values and tax base. Understanding citizens' values is also important in setting reference conditions for assessing current and future state of the stream. Do citizens value a pre-settlement, pristine environment, a stream that provides specific recreational opportunities, a MSCI score greater than 16, or a future condition that may not look anything like a natural stream (see Flat Branch Park for an example)? A socio-economic survey of citizens would provide context for how the stream may be valued beyond its impairment status. The study would use social science survey techniques similar to Baumer (2007) to evaluate community values and vision, and extend that analysis into assessment of willingness to pay for envisioned amenities.

A five year science plan

The scientific studies discussed above provide a core of efforts that will provide decision-relevant science information for Hinkson Creek (table 3), in particular to refine the "*Assess problem*" stage of the adaptive management cycle (fig. 1) to the point where relevant mitigation actions can be designed and implemented. A cost-effective approach to obtaining this information would be to prioritize and sequence studies to provide high benefit: cost and mutually supportive information. The science team completed a prioritization exercise by estimating benefit (1 low, 10 high) and relative cost (1 low, 10 high) of each study. The ratio of these two values provides an initial metric for prioritizing the studies. In addition, table 3 provides notes on duration and sequencing of the studies.

Table 3. Results of third survey of science team members, December 2017, n = 8. Prospective studies are sorted by decreasing benefit index. Benefit index should be considered as benefit to decision making presently (late 2017), with low benefit = 0, high benefit =10. Cost index was based on assignment of 0 (low) to 10 (high). Cost can be calibrated to: the least expensive cost might be in the range $0 - $10,000 for a study or report which basically already exists and only needs to be written, interpreted, and reviewed. The highest practical cost for Hinkson Creek might be a multiple year project with total cost of $500,000 to $1,000,000. The benefit:cost ratio should be interpreted with care as it is a ratio of two indices. Cell colors correspond to high values (green) to low values (red).

Serial					
Serial Number	**Description**	**Notes**	**Average benefit responses**	**Average cost responses**	**Average benefit:cost**
2	Colonization experiment on uniform substrate	Would provide increased understanding of roles of water chemistry and habitat effects, where, and when. Dependence on 1.	**8.6**	**5.7**	**1.5**
3	Intensive longitudinal mapping of fine sediment	This work is planned for 2018 by Boone County. Highly complementary to physical habitat assessment.	**8.4**	**3.3**	**2.5**
1	Additional analysis of existing macroinvertebrate data	Would include existing DNR data and evaluation of museum specimens.	**8.3**	**3.3**	**2.5**
9	Comprehensive chemical sampling or major or suspected contaminants.	Complementary and dependent on 1, 2.	**8.3**	**8.0**	**1.0**
7	Lidar analysis of bank retreat and sediment delivery.	Would use existing LiDAR data. Relatively low cost.	**7.0**	**2.8**	**2.5**
14	Role of physical habitat disturbance in Hinkson Creek	Assess spatial distribution of stream power using existing HEC-RAS data.	**7.0**	**4.3**	**1.6**
13	Integrative watershed modeling to assess cumulative effects.	Intended to assess links from BMPs to stream, address how much mitigation is needed.	**6.9**	**6.8**	**1.0**
4	Transect-based surveys of bed sedimentation and erosion.	Complementary to 7, 8. Dependence on 1.	**6.7**	**6.2**	**1.1**
8	Transect based survey of bank erosion	Complementary to 7, providing more temporal information. Dependence on 1.	**6.0**	**5.5**	**1.1**
11	Evaluation of Hinkson Creek fish community responses to	Complementary to 1.	**6.0**	**5.8**	**1.0**
10	Aquatic organism exposure studies.	Complementary and dependent on 1, 2.	**5.9**	**7.8**	**0.7**
5	Photodocumentation of Hinkson Creek changes through time.	Would have ancillary benefits of outreach to public and activation of citizen science.	**5.7**	**2.5**	**2.3**
6	Evaluation of Missouri River backwater effects	Most of this analysis is completed 2/2017. Final analysis and publication needed.	**4.4**	**2.3**	**1.9**
12	Evaluation of invertebrate community responses in streams affected by Missouri River backwater.	Relevant to segmentation and regulatory context of Hinkson Creek.	**3.3**	**7.8**	**0.4**

Implementation of the Science Priorities

The priorities developed in table 3 show a strong affinity for investment in studies with high return on investment. The three highest ranking studies have the lowest costs and were developed to provide critical information to support decision making.

There are two general approaches to implementing science studies to inform management. In the sequential approach, studies are designed to provide packages of information, with each subsequent study only being implemented as the precursor study is completed and indicates it is necessary for decision making. This approach is arguably the most systematic and cost-effective because the science investment is limited to developing priority, relevant information. On the other hand, the sequential approach is also the slowest and can result in long delays in decision-making as the science process proceeds. In contrast, a parallel approach can be used that will invest in carrying out multiple studies at the same time. In the parallel approach some of the information collected will not be directly relevant to decision needs and will therefore not be optimally cost-effective. The value of parallel approaches is that they minimize the time devoted to scientific inquiry. The value of information developed through parallel processes can be maximized, however, if studies are selected that are fundamental to understanding stream processes.

The studies in table 3 address fundamental information about the nature of the impairment to Hinkson Creek, but with varying benefits and costs. As information is developed in pursuit of these science priorities some questions will be answered; as a result some hypotheses and studies will become irrelevant and will fall out of the priority list. However, new information may also be developed, which can result in new hypotheses and new suggestions for related studies. Annual re-evaluations of existing information and priorities will allow the CAM process to adjust science investments to assure highest cost effectiveness. That is, the priorities in table 3 should be seen as a working set that should be re-evaluated and re-prioritized at least annually.

The second study in table 3 is underway (May 2018). The fine-sediment survey may also provide information to help understand sedimentation as a stressor on the macroinvertebrate community. The Science Team endorses completion of this study assuming most of the effort will be a contribution from Boone County Resource Management staff. Additional resources may be necessary to review and publish the study so the stakeholders can be confident that the information is reliable and in the public domain.

The third study in table 3 – additional analysis of macroinvertebrate data – has been discussed by the Science Team for several years and a proposal is presently under discussion. One of the benefits of the study would be confirmation that all relevant macroinvertebrate data have been evaluated. An additional important potential of the study is that more samples and additional approaches to understanding species' tolerances may yield diagnostic understanding for the cause(s) of impairment. Because of the potential to aid in diagnosis, this study is seen as a prerequisite for others in table 3. The impediment to this study – and all of the remaining studies in table 3 – is identifying resources and expertise.

Several studies in table 3 relate to specific hypotheses about physical processes being operative stressors. Both are also based on the fact that substantial costs of data acquisition (LiDAR and HEC-RAS results) have already been expended. The LiDAR survey (study 7) addresses the specific hypothesis that sedimentation is a substantial stressor and that streambank erosion is an important contributor of sediment to Hinkson Creek. It may be cost-effective to delay this study until the macroinvertebrate analysis (study 1) is completed because those results may provide guidance about the importance of sedimentation. The evaluation of physical disturbance study (14) has the potential to identify parts of Hinkson Creek that would, on average, experience greater or smaller amounts of stream power, which can be predictive of bed erosion or bed sedimentation. Similar to the LiDAR survey, it may be more cost-effective to wait for results of the macroinvertebrate analysis, which may indicate a more specific role for bed disturbance in structuring the macroinvertebrate community. Importantly, both of these studies may have important ancillary benefits to stream management beyond understanding impairment of the macroinvertebrate community.

Study 2 in table 3 is notable because it has the highest average benefit index (8.6) but because of perceived high costs, it also has a lower benefit:cost ratio. If successfully completed, this study would provide important diagnostic information to discriminate between the two dominant classes of impairment, physical and chemical. Because of the importance of the information content, the case could be made that it should start immediately after the macroinvertebrate analysis (study 1) and before other studies. Or, it could be started in parallel with the other studies so the important data will be available for reprioritizing science and management actions as early as possible. The study is also notable for requiring more time, expertise, and a logistically demanding field approach.

Similarly, Study 9 – comprehensive chemical sampling – ranks high in benefit, but scores low in benefit:cost because of high costs.

Study 13 is notable because of its potential integrative role. As indicated in the section of this report on monitoring, assessment and evaluation of BMP projects, one of the fundamental questions is whether a project can be scaled up to have a measurable influence on the creek. The main mechanism for scaling up is watershed modeling. Hence study 13 can be seen as providing a framework for information assimilation for the entire CAM process on Hinkson Creek. The study ranked relatively low because of relatively high estimated cost. Notwithstanding this low ranking, the CAM partners may perceive greater value of this study as a planning tool compared to its benefits as a science study.

At present (May 2018), the Science Team recommends continuing with the intensive longitudinal mapping of fine sediment (project 3, table 3), which is underway by the County. The team will also submit a short preproposal to the Action Team for a project for additional analysis of existing macroinvertebrate data (project 1, table 3). These two projects share the highest benefit:cost index and some of the highest estimated benefits.

The Science Team will initiate two additional efforts during spring 2018. The first is to acquire GIS data for stormwater infrastructure for the campus, city, and county. These data will be added to existing GIS layers to improve the Team's ability to evaluate the spatial distribution of stressors and indicator responses (essential for project 3). The second will be to initiate discussion with the Action Team about feasibility for a field-based experiment to evaluate benefits of reduced chloride loading from road salt. Although evidence is strong that chloride from road salt applications is a likely chemical stressor on Hinkson Creek, the Team has been conflicted about whether a field-based experiment (or demonstration project) would be feasible in the watershed because of lack of experimental controls and public safety concerns. The objective of this experiment/demonstration would be to evaluate a) whether applications or formulations can be optimized through best-management practices to reduce chloride concentrations and loads while maintaining safe streets, sidewalks, and parking lots and b) whether that level of chloride reduction be significant in reducing exposure to stream organisms.

Science Process and CAM

The promise of CAM is that investment in evidence-based learning – in a collaborative management environment – is the most cost-effective route to solving difficult environmental problems. For CAM to work, science information must be perceived by all Stakeholders as credible, unbiased, and relevant to decisions. To achieve this, information must be:

- peer reviewed for quality;
- vetted by management as relevant;
- freely available in the public domain;
- provided in a timeframe that is relevant to management decisions;
- clearly and frequently communicated to engaged Stakeholders.

Numerous CAM efforts have realized that to achieve these properties, the science effort needs to be guided strongly by CAM priorities. The CAM process for Hinkson Creek is at a scientific juncture and the case can be made that the process needs to be reinvigorated. Five years of investment has provided a strong foundation and useful insights into key physical and ecological processes. On the other hand, we are only marginally closer to understanding the causes of impairment(s) compared to 2012. The Science Team supports a transition into a new phase with an emphasis on directed, decision-relevant science.

Provision of science information needed by the Hinkson CAM process ultimately will require directed application of resources to specific science questions. We suggest the following changes to the CAM process:

- Increase interaction between the Stakeholder Team and the science and Action Teams. Although Action Team members regularly attend Science Team meeting and participate in discussions, Stakeholders have only rarely attended. As a result, Stakeholders have not been aware of the range of discussion on scientific progress and communication of science to the Stakeholders has suffered. Moreover, the formal format of stakeholder meetings has minimized scientists' input. Science team members should regularly attend the stakeholder meetings and engage in the conversation. Joint meetings of the three groups should occur to ensure communication and common understanding.

- Develop a systematic and periodic process for funding decision-relevant science. The process should evaluate proposals based on relevance to management decisions, quality of science, and cost effectiveness. The most direct approach to attracting high-quality science proposals is a request for proposals (RFP) process (assuming that appropriate funds are available to carry this out). A realistic level of investment will be required to make progress on critical science questions.

- Require quarterly progress updates for all funded projects. Require written annual reports to be submitted to the Stakeholders, and the Action and Science Teams.

- Require that data collected through funded projects be freely available to the public and distributable after a reasonable quality-assurance time period.

- Develop a peer-review process to support Hinkson Creek CAM decisions. This technical review process would be specifically for vetting the value of the information for the Hinkson Creek CAM process.

    - The Science Team may be able to carry out the review function.

    - Two factors need to be considered. One is that Science Team's work been essentially voluntary from the beginning, and increasing work load may not continue to be possible on a voluntary basis. The second factor is the need to ensure that the reviews are viewed as independent and fair.

    - Faculty at the University of Missouri, USGS, MDC and DNR who are not directly involved in the Hinkson Creek work could perform much of this review work, if the workload is well distributed.

Financing Science Efforts

These suggestions are made with full knowledge that they will be challenging to fulfill. Paramount is the need for a reliable, substantive source of funds for science efforts.

Effective CAM requires strong engagement from scientists, and many programs have struggled with how to structure the science input to accomplish the best engagement. For academic scientists, the engagement and sharing required by CAM can be counter to typical academic reward systems. Some specific CAM research efforts may fit well within a 2-4 year graduate school cycle, but others require longer, persistent commitment to maintaining data systems as in long-term monitoring. Some institutions may be good at collecting data, whereas others may be better at analyzing and integrating. Hence, many CAM programs distribute some science projects to universities, some to agencies, some to private sector science providers, and some to internally paid staff. The Hinkson Creek CAM process will need to strategize for the optimum distribution.

Structurally, the CAM process needs to have a dedicated person or team that serves to assimilate information, provide opportunistic and necessary data analysis, assure QA/QC, address data management and archiving concerns, communicate results with the Stakeholders, Action, and Science Teams, and produce annual reports. It is notable that the CAM agreement (Hinkson Creek Collaborative Adaptive Management Partners, 2012) states that the Science Team is responsible for these functions, and in particular for synthesizing reports; however, the Team lacks resources to carry out these functions. Ability to function as indicated in the CAM agreement would require support of one or more staff members with technical stream-ecology or hydrology expertise. As a starting point, this is estimated at about 1 FTE @ about $75,000/year. The costs of the seven science topics outlined in the 5-year plan have not been evaluated in detail, but the minimum annual cost is likely to be about $150,000 per year, for a total annual cost on the order $225,000. These costs assume most of the work is done through university contracts or consultants.

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