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Optical Water Quality and Human Perceptions of Rivers

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Optical Water Quality and Human Perceptions of Rivers

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Environmental Dynamics

by

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Abstract

Understanding water quality dynamics in recreational rivers is integral in shaping management strategies that maintain ecosystem health, perceived value and appeal, and regional economic significance in a changing environment. Optical water quality describes the behavior of light in water as governed by its physical and chemical composition, and is among the strongest influences on human perceptions of water quality. Ethnohydrology is the study of culturally constructed knowledge and understanding of water. This work is the culmination of an interdisciplinary approach to water resources research—integrating optical water quality and ethnohydrology methods to recognize the intersection between measured water quality and visible characteristics influencing human perceptions. Relationships among particulate concentrations as a function of the hydrograph during receding flow in five popular recreational rivers of the southwestern Ozarks of Arkansas, USA were dependent upon catchment characteristics, and optical water quality measures may be well-suited for describing these dynamics in the absence of more intensive monitoring programs. Measurement of horizontal black disk visibility was a particularly accessible and intuitive scientific tool for characterizing optical water quality and suspended sediment variability. Analyses of 167 surveys and pile Sorts deployed at regional events indicated that, despite some variability, individuals may use similar cognitive processes to discern differences among images of aquatic conditions in rivers, and these judgments can be directly linked to optical water quality measurements. This work suggests important physical and chemical parameters of water quality may be communicated meaningfully across stakeholders in terms of how they relate to visible attributes, thus expressing water quality in terms of its true meaning to society and the environment.
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Finally, I thank Donald Smith—in spite of a thousand miles, his patience and support never faltered.
Dedication

This dissertation is dedicated to all those who are drawn to the water and find themselves home.
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may be some differences in style, and material may be repeated.

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I. Introduction

The Clean Water Act [US Congress 1972] explicitly protects US waters for aesthetics and recreation. Yet, these ideals can be difficult to define in terms of measurable water quality parameters. We know from previous research that stakeholder engagement supports more effective management programs [Reed 2008], and that human perceptions are based on visual cues [Happs 1986]. However, much of the existing research reveals more about preference than cognition—it tells more about what people like and dislike, rather than about the thought processes that go into making those judgments [Zube 1982].

In April 2016, the US Department of the Interior announced an initiative to “document the full value and contributions of outdoor recreation to the American economy” [US Department of the Interior 2016b]. The program will be the first time the US Federal Government will analyze the economic influence of the Nation’s natural resources for recreation [US Department of the Interior 2016a]. The Outdoor Industry Association [2012] estimated outdoor recreation in the US to contribute $646 billion annually, and 6.1 million jobs. In Arkansas, outdoor recreation accounts for $10 billion in annual consumer spending, and generates 126,000 direct jobs [Outdoor Industry Association 2012b]. The desirability, thus economic influence, of water bodies for recreation can only be understood by considering human perceptions and how they may be influenced by changes in the aquatic environment.

Optical water quality describes the behavior of light in water as governed by its physical and chemical composition [Kirk 1988], and is among the strongest influences on human perceptions of water quality [David 1971, Cottet et al. 2013]. Ethnohydrology is the study of the culturally-constructed knowledge and understanding of water [Back 1981, Gartin et al. 2010].
This work is the culmination of an interdisciplinary approach to water resources research—
integrating optical water quality and ethnohydrology methods to recognize the intersection
between measured water quality in recreational rivers of the southwestern Ozarks and visible
characteristics influencing human perceptions. This research seeks to unite what is measured
with what is perceived. The intention is to enhance communication among stakeholders and the
effectiveness of surface water conservation programs.
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Reed, M. S. (2008), Stakeholder participation for environmental management; A literature review, *Biological Conservation*, 141, 2417–2431.


II. Optical Water Quality and Human Perceptions: A Synthesis

This chapter is published as:

Abstract

Because humans have such strong physical and emotional connections to water in the environment, it follows that individuals and groups will have strong ideas and expectations of that environment that must be related to visible features. Optical water quality describes the scattering and absorption of light in water as governed by its dissolved and particulate composition. Mineral suspended sediment, dissolved organic matter, and living and nonliving particulate organic matter have different influences on the behavior of light in water. The physical sciences endeavor to define variability in water quality, be it natural or anthropogenic, for use in water resource management. However, a more holistic approach to water resource management is becoming increasingly advocated, which requires investigation of the human dimension. The directly visible attributes of color and clarity of water are among the strongest influences on human perceptions of water quality. The observed environment is perceived through cognitive processes that are defined by spiritual and cultural beliefs and evolve with personal experience, creating the mental model. Water color and clarity can provide a critical link between water quality and human perceptions. Ethnohydrology is the study of culturally constructed knowledge and understanding of water. An interdisciplinary approach, integrating optical water quality measurement and ethnohydrology methods, may help achieve better awareness, communication, participation, and support in water resource management and sustainability endeavors.
Introduction

Knowledge and evaluation of human perceptions of environmental quality have long been pursued in diverse disciplines including landscape design, environmental sociology, psychology, and property valuation. While there is substantial evidence that perceptions and objective measures differ, the underlying factors of this divergence have been neglected [Artell et al., 2013]. Researchers have sought to identify what characteristics of natural environments trigger certain responses in viewers [David, 1971; Zube et al., 1982; Happs, 1986], but have not established how those responses relate to continuous water quality datasets. Because of the way light behaves in water, we are presented with a unique opportunity to integrate the biophysical and ethnological into a more comprehensive understanding of the dynamics and broader implications of the immense variability of inland waters.

The term ethnohydrology was introduced by William Back [1981] in 1981 as a subset of ethnoscience that describes the observation and interpretation of hydrology as a cultural construct. It was later described by Gartin et al. [2010] as the cultural knowledge of water. Ethnohydrology now includes investigations that seek similarities and differences in cultural knowledge, evaluation, and perceptions of water quality. Cultural values should be considered among ecosystem services [Brauman et al., 2007] to achieve a necessary holistic approach to water resource management that includes the human values of place, nature, and permanence [Lant and Mullens, 1991]. The capacity to communicate effectively between human groups with vested interest in water resources hinges on understanding the nature of water quality perceptions and the extent to which they vary intra-culturally.

Color and clarity are the fundamental links between water quality and human perceptions (Figure 1). At this interface arises the human dimension that often confounds ecosystem

6
management and communication between stakeholders, but through which ecosystem status and human perceptions may be interpreted. Figure 1 can be approached from the top, suggesting cultural and spiritual values dictate human interactions with water in the environment. From the bottom, Figure 1 is a conceptual model of the causal relationships between measurable ecological consequences of climate, geology, and land use in the watershed. The arrows in Figure 1 signify how human perception relates to measured parameters of water quality, primarily through the visible attributes of color and clarity in water. The dashed line in Figure 1 suggests there is a weaker understanding of the relationship between measurable ecologic indicators and human perception of the environment.

In this paper we discuss the relevant literature concerning optical water quality (OWQ) and human perceptions of water quality. First, we provide an overview of some common methods of scientific evaluation of OWQ. Second, we review works investigating how human perceptions of water quality are influenced by some of those very same variables. Finally, we present a case for the integration of research methods to directly relate quantitative measures of water quality to the visible cues that influence human perceptions. It is only with a strong understanding of how human evaluation of an environment relates to quantifiable environmental assessments that effective communication between all stakeholders can be achieved, thereby lending support to water resource management. Ecology and human perceptions are intrinsically linked within a much larger context (Figure 1), but our understanding of this connection requires a truly interdisciplinary approach that includes physical and social science to achieve more successful communication and sustainability in water resources.
Optical properties of water

Hydrologic optics

When light strikes a waterbody, the first major change occurs at the air–water interface. Light either enters the water, or it is reflected. The specifics of this interaction are governed by the instantaneous light field and waves or ripples on the water’s surface [Jerlov, 1976]. By Fresnel’s Law, when the angle of the sun is low, more light is reflected [Wetzel, 1975], creating that mirror image so common in photographs of sunsets on the water. Less reflection occurs when the sun is higher or cloud cover dampens incoming sunlight [Preisendorfer, 1976] and the water’s characteristic color and clarity become evident. Color and clarity, as perceived by the human eye, are controlled by absorption and scattering of the different wavelengths of visible light. Wavelengths that are absorbed are no longer available as light to be perceived by the human eye; those that are scattered back to the eye give the perceived color. Greater clarity occurs when light is allowed to continue in a forward direction, escaping absorbing and scattering obstacles and illuminating to a greater distance [Davies-Colley et al., 1993] (Figure 2). Color and clarity in water are ultimately determined by the specific absorption and scattering properties of substances within the water.

Absorption is the process by which photons of light of specific wavelength come into contact with a molecule or compound and their energy is converted, usually to heat or chemical energy by photosynthesis [Kirk, 2011]. The absorption coefficient ($a$) describes the probability that a photon will be absorbed as it travels along its path [Davies-Colley et al., 1993].

$$a = \frac{\Delta \Phi / \Phi}{\Delta r}$$  \hspace{1cm} (Equation 1)
The absorption coefficient, in units of m\(^{-1}\), is the proportion of the change in radiant power, in watts (W), by absorption (\(\Delta \Phi_a\)) to total radiant power entering the system (\(\Phi\)) over a distance (\(\Delta r\)). Absorption coefficients of inland waters can vary by several orders of magnitude based on concentrations of dissolved and particulate matter [Mobley, 1995]. Absorption in water increasingly removes light in the shorter wavelengths [Jerlov, 1976]. The sum of absorption coefficients of the dissolved and particulate contributions at 440nm in natural waters has been measured from nearly pure water up to 19.99 m\(^{-1}\) [Kirk, 2011].

Scattering occurs when photons are deflected by molecules or particles in the medium. The particular wavelengths that are scattered back to the eye give the perceived color. Similar to the absorption coefficient, the scattering coefficient (\(b\)) describes the probability that a photon will be scattered, i.e., diverted from its path, as it travels through the medium [Davies-Colley et al., 1993].

\[
b = \frac{\Delta \Phi_b}{\Phi \Delta r}
\]  
(Equation 2)

The scattering coefficient, in units of m\(^{-1}\), is the proportion of the change in radiant power by scattering (\(\Delta \Phi_b\)) to total radiant power entering the system (\(\Phi\)) over a distance (\(\Delta r\)). Scattering coefficients in inland waters have been reported between 0.29 and 90.8 m\(^{-1}\) [Kirk, 2011]. Ultimately, the beam attenuation coefficient (\(c\)) describes the cumulative effects of absorption and scattering and gives a full account of the optical properties dependent upon composition of the medium through which light is travelling (Equation 3).

\[
c = a + b
\]  
(Equation 3)

Visual clarity is greater, and the beam attenuation coefficient is lower, when more photons escape absorption and scattering [Davies-Colley et al., 1993].
Irradiance (E) is an instantaneous radiometric quantity [Mobley, 1995] that describes the amount of radiant energy per time arriving on an infinitesimal surface [Jerlov, 1976]. It is the radiant power (Φ) per unit area (A), in watts m$^{-2}$, from all directions and declines exponentially with depth [Jerlov, 1976]. For the purposes of this discussion we are interested in energy in the form of wavelengths of light within the visible spectrum, between 400 and 700 nanometers, $E_{\text{vis}}$.

$$E_{\text{vis}} = \frac{\Phi(\text{vis})}{A} \quad (\text{Equation 4})$$

Vertical attenuation coefficients, known as the various K-functions in hydrologic optics, describe the change in light with depth in water. The irradiance attenuation coefficient, K, describes the proportion of incoming irradiance that is lost ($\Delta E_{\text{vis}}/E_{\text{vis}}$) with water depth ($\Delta z$) and is expressed in units of m$^{-1}$.

$$K = \frac{\Delta E_{\text{vis}}}{E_{\text{vis}} \Delta z} \quad (\text{Equation 5})$$

The irradiance attenuation coefficient is an instantaneous value that is dependent upon both composition of the water and the present light field.

The behavior of light in pure water is constant (at constant temperature and pressure) and predictable [Jerlov, 1976]. The absorption spectrum of pure water [Pope and Fry, 1997] (Figure 3) is a result of the vibrational energies achieved by hydrogen bonds between water molecules [Nassau, 1983]. The greatest absorption within the visual spectrum occurs at the longest (red) wavelengths, and the greatest scattering at the shortest (blue) wavelengths [Smith and Baker, 1981]. This is what gives pure water its pale blue color [Kirk, 2011]. Because water so strongly absorbs light, incoming light will be completely attenuated with sufficient depth in even the purest water. The variability that gives a body of water its particular ecological or esthetic optical
characteristics, i.e., perceivable color and clarity, depends on its composition, which is governed by climate, geology, seasonality, land use, and non-point and point source pollution.

The behavior of light in inland waterbodies is fundamentally governed by the water’s dissolved and particulate composition, and the geometric structure of the light field [Tyler, 1978]. Properties dependent only upon the composition of the water are known as inherent optical properties (IOPs); conversely, properties that are a function of the instantaneous light field are known as apparent optical properties (AOPs) [Preisendorfer, 1976]. The IOPs describe absorption and scattering of light by water and the various components that exist in the water—ultimately, the beam attenuation coefficient. The AOPs depend on the IOPs, as well as on the quality of ambient light as influenced by angle and intensity at the air–water interface. AOPs are among the most commonly measured optical properties in water (e.g., Secchi depth and photosynthetically available radiation) and can change dramatically based on weather or physical conditions of the water’s surface [Mobley, 1995]. Jerlov [1976], Mobley [1995], and Kirk [2011] provide comprehensive examinations of hydrologic optics theory. For this discussion, we focus on the optical characteristics that are most influential at the intersection of ecology and human perception. Thus, the focus here is on light attenuation from the perspective of the human viewer.

**Constituents affecting optical water quality**

Inorganic and organic particles attenuate light at different magnitudes based on their size, shape, and composition [Gippel, 1995], each of which has implications on both habitat suitability and aesthetics. Mineral suspended sediments (SS) are the inorganic portion of total suspended solids and strongly scatter light. Organic material can be bound to mineral particulates, perhaps absorbing light and contributing to color [Kirk, 2011]. The size and shape of particles in
suspension are the dominant influences on light scattering [Jerlov, 1976; Gibbs, 1978]. Fine clays, with a flatter crystalline structure, strongly scatter light and can remain suspended indefinitely [Julian et al., 2013]. Heavier and more rounded sediments settle rapidly and the remaining clay minerals in suspension can play a distinct role in light attenuation with time after a suspension event [Davies-Colley et al., 1993; Julian et al., 2008].

Nonalgal particulate organic matter (NPOM) are responsible for both absorbing light of shorter wavelengths and scattering light, causing a yellow hue in water color [Davies-Colley et al., 1993]. NPOM more strongly absorb light than SS particles of the same size and typically have lower density than SS, causing NPOM to remain suspended longer [Davies-Colley and Smith, 2001]. Phytoplankton are an important proportion of the living portion of suspended particulate organic matter. They are major absorbers of light, primarily in the blue and red wavelengths [Mobley, 1995], and strongly scatter green and yellow light [Davies-Colley et al., 1993]. The specifics of light attenuation by phytoplankton depend on species, pigment composition, size, and orientation of cells [Kirk, 1976]. Chlorophyll a, the primary photosynthetic pigment in phytoplankton, can give water a green hue [Davies-Colley and Close, 1990]. Consequently, it is this feature that may be used to enhance capabilities of remote sensing of water quality [Kirk, 2011].

Chromophoric dissolved organic matter (CDOM), or gilvin, is made up of humic substances leached from soils and decomposed plant matter [Kirk, 2011]. Julian et al. [Julian et al., 2008] found that dissolved materials do not strongly influence clarity, but Davies-Colley and Close [1990] found that they do contribute significantly to color. This occurs because scattering by CDOM is minimal and absorption is predominantly relegated to the shorter (blue)
wavelengths [Kirk, 2011], allowing water to simultaneously appear clear and with color [Davies-Colley et al., 1993].

**Measures of color and clarity**

*Secchi Depth*

Probably the best-known method of measuring water clarity in the environment is by Secchi disk. First established as an all-white disk for field measurement by Pietro Angelo Secchi in 1865 [Cialdi and Secchi, 1865], its history allows it the distinction of being one of the longest recorded water quality observations. Though yet to be precisely standardized [Smith, 2001], the traditionally used Secchi disk is 200mm, weighted plastic, with alternating black and white quadrants (Figure 4a). Usually, it is lowered into the water from a boat, raised, and lowered again to determine the depth at which visual extinction occurs, the Secchi depth ($z_{SD}$). The Secchi disk is a simple, inexpensive method and is relatively intuitive, in that it defines a tangible distance that is easily communicated.

Secchi depth is dependent upon both IOPs and AOPs, and can be used to estimate the value of downward irradiance attenuation [Kirk, 2011]. The quantity $c + K$, in units of m$^{-1}$, is a depth-averaged value of visible light extinction that can be determined from Secchi depth; additional optical measurements are required to isolate either variable [Preisendorfer, 1986].

$$c + K = \frac{r}{z_{SD}}$$

(Equation 6)

While several studies have attempted to develop an empirical relationship between Secchi depth and light attenuation, the relationship can be highly variable. Theoretical work by Tyler [1968]
gives $\Gamma$ a value of 8.69, assuming 86% reflectance of the Secchi disk and 2% reflectance at the water’s surface.

A shortcoming of the Secchi disk is its limitation to waters of a depth greater than $z_{SD}$ without strong flow. Other weaknesses of the Secchi method are mostly due to its reliance on AOPs rather than IOPs, the factor complicating the establishment of an empirical value for $\Gamma$. Secchi depth can be influenced by the reflectance of the disk itself, the angle and intensity of the sun at the time and location of measurement, cloud cover, and turbulence on the water’s surface [Preisendorfer, 1986], all of which were recorded in Secchi’s own writings [Tyler, 1968]. Accordingly, Preisendorfer [1986] explicitly offers ten mathematically derived laws of the Secchi disk that should be acknowledged by users. With their acknowledgement, the effects of AOPs can be minimized to functionally introduce low relative errors in Secchi depth measurements [Davies-Colley et al., 1993].

**Horizontal black disk visibility**

Davies-Colley [1988] introduced the black disk visibility method for horizontal measurement of water clarity. The device consists of a black, matte disk on a pole and an inverted periscope for underwater observation of the disk (Figure 4b). The distance at which the disk is no longer visible ($y_{BL}$) is determined by gradually moving the disk away from the viewer until its silhouette goes visually extinct [Davies-Colley, 1988a]. This parameter is what recreational users would see when they open their eyes underwater.

Because the black body is not reflective and observation is made horizontally underwater, visibility depends only on the IOPs and the limitations of the human eye with respect to brightness and contrast. Sun angle or intensity does not introduce significant variability in black
Based on well-developed radiative transfer theory by Tyler [1968], Duntley [1963], Jerlov [1976], and Preisendorfer [1976], and the fact that contrast visibility for human sight can be considered constant under ample daylight [Duntley, 1963] (corresponding to luminance values greater that 3.43 candelas per square meter [Blackwell, 1946]) an empirical relationship can be derived with a unitless constant of proportionality, $\Psi$.

$$ c = \frac{\Psi}{\Psi_{BD}} $$

(Equation 7)

Experimental work by Davies-Colley [1988] and further investigation by Zaneveld and Pegau [2003] give and approximate value of 4.8 for $\Psi$, which allows us to estimate the beam attenuation coefficient, in units of $\text{m}^{-1}$, from horizontal black disk values.

Steel and Neuhausser [2002] noted possible variability based on observers and the somewhat cumbersome nature of the periscope as weaknesses of the method. The black disk method also ideally requires two people, unless the target can be stably fixed into position. Even with its limitations, the horizontal black disk is a simple, inexpensive device for measuring water clarity and is especially useful in shallow, rapidly flowing waters. The horizontal black disk method has not been widely used outside of New Zealand. However, Zaneveld and Pegau [2003] proposed that the black disk be the standard for measuring underwater visibility for military operations.

**Turbidity**

Turbidity is a commonly measured and referenced parameter in OWQ. However, the word turbid is also used colloquially as a descriptive attribute of water. A turbidimeter is an electronic device that optically measures light attenuation. Nephelometric measurement is related to light scattering [Kirk, 2011] and is reported as either formazin nephelometric units (FNU) by
ISO method 7027 or nephelometric turbidity units (NTU) by US EPA Method 180.1 [Anderson, 2005a]. Turbidity can also be reported in attenuation units (AU) when using absorptiometric devices [Anderson, 2005a]. Though the measure is essentially dependent upon IOPs, it is important to note that the units are an arbitrary, relative index of clarity [Smith and Davies-Colley, 2002] that cannot be used to estimate values of fundamental optical properties [Kirk, 2011] without deriving an empirical relationship between variables. Also, turbidity meters can vary substantially based on specific instrument design [Anderson, 2005a; Lewis et al., 2007a]. Because it is so commonly measured, turbidity can be valuable in comparative studies. Turbidity has been shown to be a worthwhile proxy for suspended sediment concentration, but the precise relationship can differ by a factor of four as a result of particle size distribution and relative composition of organic and inorganic matter [Gippel, 1995], which varies seasonally and spatially [Kronvang et al., 1997].

Munsell Color

The Munsell color system, commonly used in soils classification, has occasionally been used [Davies-Colley and Close, 1990; Smith et al., 1995a; Davies-Colley et al., 1997] to quasi-quantitatively assess water color and is a simple, practical method related to the characteristics actually perceived by a viewer. Munsell’s hue circle divides color into 100 steps of equal visual change, categorizing with five principal and five intermediate hues (Figure 5, inner ring). However, the five principal hues of the Munsell system (red, yellow, green, blue, and purple) imply a fundamental color categorization that is not necessarily universal [Hardin and Maffi, 1997; Dedrick, 2015]. In practice, the investigator views the water alongside Munsell color plates and determines the best visual match. Munsell hue can be identified numerically (Figure 5,
outer ring), though the 40 alphanumeric hues (Figure 5, shaded ring) are preferred [American Society for Testing and Measurement, 1968]. Additionally, the system provides for brightness and saturation, respectively termed value and chroma [Williamson and Cummins, 1983]. Importantly, the values on the Munsell scale are arbitrarily assigned and not representative of any other quantitative optical value, such as those that might be determined by spectrophotometry, and do not correspond well to colorimetric specification [Williamson and Cummins, 1983]. The Munsell system is designed for use with opaque materials [American Society for Testing and Measurement, 1968], thus, while it is perhaps the most practical method, its use for classifying water color may be problematic.

**Visual cues influencing human perceptions**

_Cognition_ is the process by which objects are recognized, identified, and classified [Hatfield, 2009], but the process itself cannot be directly observed in the human mind [Dougherty, 1985]. _Perception_ is the process of mentally capturing, processing, and assigning meaning to an observation or experience [Garner, 2007]. Environmental perceptions are formed by both cognitive and emotional criteria within a cultural framework [Cottet et al., 2013]. They are dependent upon expectations determined by particular relationships with the landscape [Zube et al., 1982]. Perceptions of water quality (WQ) are influenced by personal experience, socioeconomic and educational status, environmental knowledge, attitudes, proximity to, and frequency of contact with water in the environment [Artell et al., 2013]. It is not suitable to try to use a single of these variables to broadly determine public perception because objectivity is so difficult to achieve [Happs, 1986]. But, a better understanding of how WQ perception and cognition relate to actual WQ is important because human perception directly affects human
behavior [Artell et al., 2013]. The perceived environment may well be a stronger influence on behaviors than the physically defined environment [Daniel, 1976], and visual parameters have been shown to dominate perception [David, 1971]. Cottet et al. [2013] found that perceptions of both lay-people and experts were most strongly influenced by visual criteria. To complicate the matter, judgments of WQ may also be influenced by visual assessment of the surrounding landscape, with little regard to optical water characteristics.

_Color_

Color is a dominant feature in human perception of water [Smith et al., 1995a]. When asked how they judged WQ, residents at riverside campgrounds in France listed color most often [Moser, 1984]. Though it may seem unsurprising, it is worth stating that blue water was preferred to yellow water [Smith et al., 1995a], and people rejected brown water [Cottet et al., 2013]. Unusual color was perceived as an indicator of bad WQ [House and Sangster, 1991]. Murky or dark water was perceived as suggestive of pollution [David, 1971].

In brightly lit, relatively deep waters, recreational users were able to describe water hues well [Smith et al., 1995b]. A study of campers at Minnesota lakes linked colors from green to blue to “clear” to more favorable assessments of WQ [Nicolson and Mace, 1975]. Discolored water, with industry as the most commonly accused cause, was more influential even than litter in participants’ rating of pollution [Dinius, 1981]. Smith and Davies-Colley [1992] used Munsell color swatches to classify hues in recreational waters and relate them to user perception. They determined that people generally responded negatively to yellow, were just tolerant of green-yellow, and considered green to blue as suitable for bathing. Though some users, when being able to justify yellow water as naturally occurring were more accepting of the hue [Smith et al.,
1995a]. Still, highly turbid, brown water, regardless of its perceived naturalness would be avoided [Smith et al., 1995b].

Clarity

Water clarity can be of importance in human perceptions for several reasons. In one study, personal safety was the most mentioned concern of primary contact users, with references to clarity in approximately half of the responses as the way to gauge safety [Smith et al., 1995a]. Clarity (“can see river bottom”) was perceived as a strong indicator of good WQ [House and Sangster, 1991; House and Fordham, 1997]. Clarity is also related to perceived health of the aquatic environment. In a study comparing cultural monitoring approaches of the Māori people with common scientific measures, the proportion of streams in specific health categories defined by turbidity most closely resembled those defined by cultural indicators [Harmsworth et al., 2011]. Clarity is a dominant factor in user satisfaction as well. Kooyoomjian and Clesceri [1974] reported fewer complaints from users of clear, oligotrophic lakes when compared to those of eutrophic lakes. Favored riverscapes are those with clear, flowing waters [Gregory and Davis, 1993; Cottet et al., 2013].

Studies uniting specific continuous WQ variables with detailed human perceptions are somewhat rare. However, Secchi depth has been concluded as the best single measure to use when modeling recreational site selection [Egan et al., 2009]. In studies of recreational users of rivers and lakes in New Zealand, Smith et al. [1991, 1995a] linked black disk visibility >1.2 m to bathers’ assessment of suitability. However, visibility greater than 2 m did not appear to significantly alter individual perceptions [Smith et al., 1995a]. Clarity rating scores by field research crews was the strongest predictor of recreational impairment and were correlated with
measured water quality variables [Smith et al., 2015]. Smith and Perrone [1996] investigated human sensitivity to changes in water clarity in a laboratory setting and found that sensitivity was higher at low turbidities. But, the perception of clarity may be influenced by other visual cues and factors meaningfully into respondents’ evaluations of WQ [Smith et al., 1995a]. High clarity was positively viewed, though the absence of clarity made respondents defer to color as a defining criterion [Moser, 1984].

Other influences

Perhaps the strongest feature influencing perception of WQ is odor. However, people have varying sensitivities to odors. After a major fish die-off at a lake in Minnesota, Nicholson and Mace [1975] noted a strong smell of rotting fish; 45% of respondents said they smelled dead fish, 51% reported no smell. Moser [1984] found that when a bad odor was present, WQ was generally judged to be poor and no other criteria were needed. Dinius [1981] found that the mere expectation of odor, as perceived from images presented to respondents, was the best predictor of perceived pollution.

Notably, the presence of algae and water plants affects perceptions [Moser, 1984]. A survey of adults in Wisconsin showed algae and green scum as perceived indicators of pollution for 40% of respondents [David, 1971]. Thirty two percent of Minnesota respondents reported the same [Nicolson and Mace, 1975]. It was the most common response in both studies. In a study of Phoenix residents, 68% of respondents listed algae as an indicator of poor WQ [Gartin et al., 2010]. However, submerged vegetation can have strong aesthetic value. A waterbody can be perceived as healthier when it supports submerged vegetation [House and Sangster, 1991; Cottet et al., 2013].
Landscape art in the mid-nineteenth century brought forth the term *waterscape* to describe a waterbody and its surroundings [Orlove and Caton, 2010]. The observed image of the complete waterscape plays an important role in WQ perceptions [Smith et al., 1995a]. Indeed, Coughlin [1976] suggested that surroundings contribute more strongly to perceptions of water suitability than even the water itself. Herzog [1985] found that people consistently preferred spacious mountain waterscapes with rushing water. Coastal tourists in Turkey and the UK favored sites with views of expansive, natural scenery [Ergin et al., 2004]. Natural, as opposed to manicured, riverbanks are preferred [House and Sangster, 1991]. For example, a child commenting on the banks of an urban river said, “The river should be more like a river” [Tapsell, 1997]. Though, with the prevalence of human interaction and alteration of the natural environment, we may be looking ahead toward a shifting baseline of naturalness in human perceptions.

Litter gives the immediate impression of poor WQ [Dinius, 1981]. Sewage, litter, and debris have been described by respondents as both causes and indicators of pollution [David, 1971]. Children in England perceived their urban rivers as “dirty” because of the prevalence of litter, and the most frequent item listed in their ideal river space was a waste bin [Tapsell, 1997]. Aesthetic value may sometimes be evaluated solely by the presence or absence of litter [Hanley et al., 2006]. Furthermore, users who perceive poor WQ and observe litter may be more apt to participate in littering behaviors [McDaniels et al., 1998]. The presence of sewage-derived solids was among the most influential drivers of perceived poor WQ [House and Fordham, 1997].
Evaluating perceptions of optical water quality

Studies supporting human preference and psychological and effects of exposure to natural environments are abundant. The appeal of aquatic environments to humans may be an evolutionary adaptation as humans were attracted to the resources that could provide subsistence [Ulrich et al., 1991]. Because water is essential to survival, water symbolism figures prominently in human religious and secular rites, rituals, and celebrations worldwide [Fagan, 2011]. Even the simple sensory experience of immersion is expressive and fundamentally salient to the human experience [Strang, 2005]. Human exposure to nature has been shown to have substantial and lasting effects on individual emotional and physical health [Kellert and Wilson, 1993]. Interaction with the natural environment is linked to stress relief and recovery [Kaplan, 1995; Korpela et al., 2010]. Self-esteem and mood are improved more in aquatic environments than in any other green space [Barton and Pretty, 2010]. These discoveries demonstrate the need to investigate how perceptual qualities of specific environments are recognized and evaluated within human communities.

Historical studies of human perceptions of water quality

Several survey methods have been employed to explain how different groups perceive WQ. The variability shown in studies of WQ perception implies cultural influences are involved. Age and gender have been shown to influence WQ perceptions. For example, in a study of recreational users of waters in England and Wales, women were found to be more critical of WQ than men [House, 1996]. Artell et al. [2013] found that younger summer homeowners in Finland were less critical than older. Interestingly, in urban waterfronts in Vienna, Austria, Steinwelder et al. [2008] found the opposite; males and younger respondents gave worse assessments of WQ.
House [1996] found older people to initially be more critical of WQ changes, then after receiving additional information, more tolerant.

Perceptions of WQ can depend on the frequency and type of use and by spatial relationships with water. Homeowners whose permanent residence was further away from their waterfront summer house underestimated WQ, e.g., judge it as only “satisfactory” when objective measures (defined by a suite of chemical and physical criteria) classify it as “good” [Artell et al., 2013]. Alternatively, nearby residents familiar with two creeks in San Antonio, Texas believed water to be more polluted than distant, more rural residents [Brody et al., 2005]. This may be a result of a collective social construct of poor WQ in urban areas [McDaniels et al., 1998], or of the tendency of urbanites to have relatively poor ecological understanding [Gartin et al., 2010].

Recreational visitors are more likely to perceive WQ based solely upon visual cues, whereas residents’ perceptions are based on a variety of sometimes-unidentifiable sources [Happs, 1986]. Kooyoomjian and Clesceri [1974] found that homeowners at recreational lakes in New York State were less satisfied with WQ than recreationalists and suggested this was because they have more opportunity for contact. However, their lack of satisfaction may be linked to the fact that they have experienced the water in varying conditions and have a greater relative understanding of its full range of characteristics. House [1996] found frequent visitors to be more critical of WQ than those who visited less frequently. Contrarily, Moser [1984] found that long-term residents at campgrounds in France tended to evaluate WQ more favorably than objective classification, but offered the caveat that it was a place chosen by those residents for its value to them. First-time visitors must rely only on present visual environmental cues [Happs, 1986] and their less-critical perceptions of WQ may be related to the authenticity of the experience.
Often, studies appraise landscape value solely on the basis of visual responses, without investigating cognitive processing [Zube et al., 1982]. These are simply preference studies, where there is little to help define the structure of the respondent’s thought processes. Because cognition depends on learned knowledge and prior experience [Hatfield, 2009], cognitive influences on perceptions can be difficult to parse out. Nonetheless, it is this cognitive process—the mental model—that may be the most illuminating in understanding differences between stakeholders. Indeed, cultural beliefs can sometimes undermine reality [Orlove and Caton, 2010].

**Mental models**

A mental model is an internal representation of reality, the cognitive structure behind decision making and reasoning—functional yet incomplete, and personal [Jones et al., 2011b]. A mental model allows people to understand and predict their environment [Jones et al., 2011b; Lynam and Brown, 2012]. In 2001, The National Academy of Sciences suggested mental modeling as a valuable approach for addressing 21st century water issues [NRC, 2004]. Biggs et al. [2011] suggested that the concept of mental models could help in conservation planning by enhancing communication between stakeholders. Mental models can assist in understanding assumptions or differences in knowledge [Bosch et al., 2003] and can be further applied in consensus analyses to investigate the level of agreement in human–environment interactions within a group [Stone-jovicich et al., 2011].

People make judgments on their environment based on observations that fit into their own mental models [Jones et al., 2011b]. For example, the presence of fish and fishermen have been strongly associated with good perceived WQ [House and Sangster, 1991; House and
Fordham, 1997], and studies have shown observable wildlife to be important to children
[Tapsell, 1997], whereas the prospect of new experiences appeals to young adults [Herzog,
1985]. Some of the effects of an unhealthy waterway on perception of a location may fall beyond
the aesthetic, into the perceived morality of place [Coughlin, 1976]. These are cognitive
outcomes for which control is incredibly difficult and cannot feasibly be factored into discussion
without further inquiry by social science.

Mental models are not static, they continually evolve with experience and learning [Jones
et al., 2011b], but understanding them is essential for effective communication. Therefore, it may
be increasingly important to link perception with traditional WQ measurements in today’s world
of readily available information (and misinformation). For instance, Gartin et al. [2010]
identified consensus in their study of Phoenix urbanites that wells were considered a good source
of water, but that groundwater was not. Critically investigating mental models may help identify
barriers to communication, such as those that could occur in the Phoenix example. The reviews
by Jones et al. [2011] and Lynam and Brown [2012] provide examples and thoughtful discussion
of mental models in natural resource management. Elicitation of mental models can help
researchers recognize the cognitive processes that lay the foundation for perceptions of natural
systems [Jones et al., 2011b].

**Significance and implications for future research**

Environmental policy occasionally, though unsystematically, includes visual and cultural
considerations for the management of water resources. The European Union Water Framework
Directive [European Commission, 2000] calls water “a heritage” and encourages public
participation in management decisions. In the US, the Clean Water Act [US Congress, 1972] protects against degradation that affects esthetics and recreation. In Queensland, the Environmental Protection (Water) Policy 2009 [Parliamentary Council, 2009] includes cultural and spiritual significance among the values to be protected. Social and spiritual values are recognized as part of integrated management objectives in New Zealand’s National Policy Statement for Freshwater Management 2014 [Ministry for the Environment, 2014]. However, there still exist important questions: How can these values be defined? Can they be agreed upon or quantified? Quantification of human behavior, though difficult, may be integral in future water resources planning and management [Vogel et al., 2015].

Incorporating the public in decision making may introduce valuable new knowledge and approaches to hydrological science because science and society co-evolve [Lane, 2014]. In soliciting and comparing expert and non-expert mental models of water quality we might find that they are not altogether different; it may only be lexicon that separates them. Scientific measures still involve a certain amount of human decision making and judgment, rendering the concept of true objectivity somewhat tenuous [Latour, 1999]. This strengthens our argument for uniting the physical and social sciences in water resource communication.

There has been a long-standing call for interdisciplinary research in water resource management. Understanding the human response to water appearance is useful in raising public awareness and increasing involvement and support in WQ programs [Happs, 1986]. Research focused on the human dimension of water will allow us to better understand how individuals and groups might adapt their behaviors and values in a changing climate [NRC, 2004]. Elicitation of cognitive models through ethnohydrology approaches can help determine where environmental injustices are perceived [Gartin et al., 2010; Wutich et al., 2013] and contribute to a more
holistic explanation that could be used to meaningfully and productively integrate disciplines for the management of environmental resources [Ilbery et al., 1982]. The indication that visual characteristics of a waterscape so strongly influence both scientists and lay people supports the need for both physical and cognitive approaches to enhance communication. An integrative approach including both social and hydrologic sciences will allow new discoveries where human complexities may obfuscate water resource management [Braden et al., 2009]. This proposal supports a new water ethos considering communication, participation, accountability, and sustainability in water resource decisions [Chamberlain, 2008].

The structure of this synthesis was designed to facilitate the development and use of a preliminary common mental model that may help to design new research linking human perceptions to OWQ. Figure 1 illustrates how the major principles of OWQ, color and clarity, are affected by and affect broader physical and social aspects. This is obviously not an exhaustive account of the complexities of causal relationships and implications in the human–water environment. Rather, it is a functional, structural depiction that can hopefully be built upon with both physical and social science inquiry into the connections between color and clarity and human perceptions. Much in the way sociohydrology might work to broaden the understanding of water availability and access in societies [Sivapalan et al., 2012], an ethnohydrological approach will help elucidate the connections between aquatic ecology and human perceptions to achieve a much stronger comprehension of the best ways to advance the scholarship of Vernadsky’s [1945] human-inclusive biosphere.

Eliciting and investigating mental models with techniques in the social sciences can inform those items near the top of Figure 1, and hydrological sciences can chemically and physically quantify those near the bottom. Ultimately, we argue that the key to understanding the
human dimensions of water in the environment is found through the attributes of color and clarity. However, application should not be undertaken lightly for the relative simplicity of this conclusion. Future work should seek to identify cultural factors that help construct individual and shared mental models. Subsequent efforts might address how these factors influence perceptions of water quality as judged by directly visual criteria, which in turn can be tied to those visual criteria associated with variation in measured OWQ.
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Figure 1. Structural diagram demonstrating relationships involving optical water quality, at the center of which are the perceived attributes of color and clarity. Line width indicates relative strength of knowledge of the relationship. Causal relationships are arranged near the bottom. Implications and applications of advanced knowledge are near the top. The critical link between ecology and human perceptions requires further interdisciplinary investigation.
Figure 2. The processes affecting the light path as it enters a waterbody [After Kirk, 2011]
Figure 3. Absorption coefficients for pure water as measured by Pope and Fry [1997]
Figure 4. Devices used for measuring water clarity. a. Black disk and periscope b. Secchi disk
Figure 5. Munsell hue circle [After American Society for Testing and Measurement, 1968]
III. Black Disk Visibility, Turbidity, and Total Suspended Solids in Rivers:

A Comparative Evaluation

This chapter has been accepted as:

Abstract

This study compared horizontal black disk visibility, a measure of visual water clarity, to turbidity and total suspended solids concentrations in five rivers of the southwestern Ozarks of Arkansas, US in order to assess its usefulness in evaluating optical water quality. We investigated correlative relationships between black disk visibility, turbidity, and black disk visibility versus total suspended solids, and compared them to those reported in similar studies. Our results indicated that replicate measures of horizontal black disk visibility were subject to less error than replicate turbidity (coefficients of variation were 5.0% and 6.4%, respectively), and was more strongly correlated with total suspended solids concentrations than was turbidity (correlations coefficients were -0.97 and 0.92, respectively). We also assessed the validity of the black disk method as a surrogate for total suspended solids concentrations and derived a predictive model for each river in the study. The benefits of the horizontal black disk method are both scientific and practical. Horizontal black disk visibility provides a means of quantifying the beam attenuation coefficient. And, the low cost, ease of use, and usefulness in shallow rivers make the black disk method a versatile tool in water quality assessment. We ultimately conclude that the horizontal black disk method should be added to routine monitoring programs in the US, and that it be adopted by public groups involved in volunteer monitoring and water quality communication that may be limited by equipment availability or budget.
**Introduction**

The most conspicuous dynamics of water in the environment are often those relating to clarity [West et al. 2015]. Optical water quality (OWQ) is becoming increasingly regarded in inland waters because of its applications to resource management, ecosystem assessment, and remote sensing [Julian et al., 2013]. OWQ describes a water body in terms of how its optical properties influence its function in the biosphere and human environment [Kirk, 1988]. Water clarity can be considered in terms of light penetration and visual range [Davies-Colley and Vant, 1988], and is governed by the specific particulate and dissolved composition of the water and the water itself, its inherent optical properties, as well as the geometric structure of the light field [Preisendorfer, 1976; Tyler, 1978]. Light penetration is important for its role in radiation transfer, photosynthesis, and other biogeochemical reactions [Kirk, 2011]. Visual water clarity refers to the range of sighted organisms, affecting fish predation, predator evasion [Wetzel, 1975], and influencing aesthetic value and recreational desirability [West et al., 2015]. While both are integral to a full understanding of the aquatic system, our focus is on visual water clarity in the range of human sensitivity, that within wavelengths of approximately 400-700 nm [Preisendorfer, 1976].

**Measuring optical water quality**

Perhaps the best-known method of measuring visual water clarity is by Secchi disk. Its simplicity, low cost, and relationship to a tangible value (i.e., visual distance) makes it an appreciated tool in water resource management. Secchi depth (SD) can be regarded as an apparent optical property that is weakly dependent on light penetration [Kirk, 2011]. Optical theory suggests the sum of the beam attenuation coefficient ($c$) and the diffuse attenuation coefficient ($K$) can be estimated by $c + K = \frac{8.7}{SD}$ (Eq. 1) [Tyler, 1968]. Because SD is dependent
upon light attenuation with depth and instantaneous lighting conditions it should not be used to extrapolate the inherent optical properties of the medium [Preisendorfer, 1986]. Secchi disk measurement is also limited to waters of sufficient depth and low turbulence, making it difficult or impossible to use in rivers.

As an alternative, turbidity is commonly evaluated with nephelometry. Turbidity is the extent to which water lacks clarity as light is scattered by particulate matter, rather than transmitted in a straight line through a sample of water [International Organization for Standardization, 1999; Anderson, 2005; Kirk, 2011]. A nephelometric turbidity unit (NTU) is based on a calibration standard of light extinguishing material suspended in liquid, though these may not accurately represent suspensoids controlling visual clarity in surface waters. Turbidity measurement is most closely related to side scattering within a narrow range of angles centered around 90° [Kirk, 2011], though detection angles and wavelengths vary by instrument design [Anderson, 2005]. Turbidity measurement requires specialized equipment, and because of different optical designs, values from different instruments are not easily comparable [Gibbs, 1974; Hongve and Akesson, 1996; Lewis et al., 2007]. Some authors convincingly argue that when visual clarity is the attribute of interest in a water body, it should be measured directly [Davies-Colley, 1988; Smith et al., 1997; Smith and Davies-Colley, 2002]. However, automated turbidity sensors can provide continuous measurements of a wide range of water clarity, which can be very valuable in water quality assessment.

The horizontal black disk [Davies-Colley, 1988] is a method for measuring hydrological range that avoids some of the drawbacks previously described. It is a simple, low-cost device that measures underwater visibility using an inverted periscope to view a matte, all-black target (Figure 1). Because visual distance is measured horizontally, the black disk method can be used
in shallow, moving waters. It is also theoretically superior to the Secchi disk because, based on well-developed optical theory [Duntley, 1963; Tyler, 1968; Jerlov, 1976; Preisendorfer, 1976], it is strongly related to the photopic beam attenuation coefficient ($c$), an inherent optical property given by the sum of attenuation by absorption and scattering by constituents of the medium [Mobley, 1995]. The relationship, $c = \frac{4.8}{BDV}$ (Eq. 2), was determined experimentally by Davies-Colley [1988] and supported by Zaneveld and Pegau [2003]. Ideally, two investigators perform measurement, one using the viewer, and another to hold the target. Performing measurement usually requires wading into the water or gaining access by boat or dock, which can be dangerous during high flows. For solo work, the investigator may use a stake or weights to secure the target [Davies-Colley et al., 2011]. When wading is unsafe, streamside measurements can be made utilizing a clarity tube [Kilroy and Biggs, 2002]. A possible weakness of the black disk method is that it is reliant on the visual acuity of the observer. The ability of the human eye to discern contrast of a black target can be reasonably constant under sufficient light [Blackwell, 1946]. However, Steel and Neuhauser [2002] suggest some variability is possible among individuals using the method, especially as visual clarity increases, because of differences in skill or vision. For example, Eq. 2 is defined for the photopic range of normal human vision; individuals who are color blind will have different sensitivities [Zaneveld and Pegau, 2003]. Despite the theoretical and practical advantages of measuring water clarity by the horizontal black disk [Davies-Colley, 1988], especially when light attenuation by fine sediment is of concern [Davies-Colley et al., 2014], the method has not been widely used outside of New Zealand, perhaps because of lack of awareness of the method, a scarcity of comparative studies, or perceptions that the black disk is affected by biases similar to those of the Secchi disk.
Optical water quality and links to suspended sediment

In river monitoring, the quantity of interest is often the concentration of particulate matter in suspension. Effects of suspended sediment on OWQ are relevant to ecosystem health and human perceptions [Smith and Davies-Colley 2002, West et al. 2016]. Suspended sediments have come to be of primary interest in rivers around the world as watersheds are increasingly subject to disturbances by agriculture, urbanization, mining, and logging. Sediment is listed as the second-most common cause of impairment in US rivers and streams [US EPA, 2015], and the most common in Arkansas [US EPA, 2008]. In addition to effects on both light penetration and visual clarity, suspended sediment in rivers can transport adsorbed pollutants [Dodds and Whiles, 2010], alter habitats and food webs [Henley et al., 2000], and affect Earth’s material transport balance [Walling, 2006]. Optical methods of estimating sediment concentrations are often preferable because of the time and analytical cost required to measure TSS. For example, a beam transmissometer can be used to measure the beam attenuation coefficient, which Hill et al. showed can be strongly correlated to sediment mass concentrations [2011]. More commonly, turbidity is used as a surrogate measure with site-specific calibration and thorough acknowledgement of its vulnerabilities to varying particle size and composition (e.g., Gippel 1995; Kronvang et al. 1997; Jones et al. 2011).

The few investigations associating BDV with turbidity and/or suspended solids concentrations have been specific to a single site [Steel and Neuhauser, 2002], base flow conditions [Davies-Colley and Close 1990], routine monthly monitoring data [Davies-Colley et al., 2014], or across long-term median values over many sites [Smith et al., 1997]. However, Hughes et al. [2014] have reported preliminary results from their study comparing OWQ parameters during storm flow. All except one of these, the BDV–turbidity relationship examined
by Steel and Neuhauser [2002] in Washington State, US, were sited in New Zealand, though Davies-Colley and Smith [2001] include a small set of unpublished data from New York, US. Our study sought to investigate and compare relationships among horizontal black disk visibility (BDV), turbidity, and total suspended solids concentrations (TSS) using data collected after precipitation events at different sites within a relatively narrow region of the southwestern Ozarks of Arkansas, US that might be able to better characterize dependencies and further evaluate the horizontal black disk method.

Our study included critical investigation of the following hypotheses: (1) because the black disk method directly relates to the scattering and absorption properties in water, we hypothesized strong correlative relationships with turbidity and TSS; (2) because our study represents a relatively narrow geographical range of the Ozarks, we hypothesized that the five rivers would behave similarly with respect to relationships among OWQ measurements; and (3) because of the theoretical advantages of the BDV method over those of turbidity, we hypothesized that a predictive model estimating TSS concentrations from BDV measurements would be more robust than those using turbidity values as the predictor variable.

Materials and procedures

Study area

The data presented here were collected as a part of a study of receding flow dynamics in five southwestern Ozark rivers of Arkansas: Buffalo, Illinois, Kings, and Mulberry Rivers, and War Eagle Creek. Rivers in the Ozark region are characterized by steep rising limbs, in response to frontal storms, and gradual recession curves. We sampled each river near a USGS gage station continuously monitoring river stage (Table 1). All five rivers originate in the Boston Mountains
Plateau and cut deeply through the karst geology of the southwestern Ozarks. Land use in the watersheds varies from predominantly forested to urban and agricultural (US Geological Survey 2011; Table 1), representing a range of characteristics that influence flow pattern and physical and chemical properties of the rivers.

Data collection

We built the horizontal black disk device (see Supplemental Information) using mostly materials readily available at an area hardware store at a cost of approximately $50. For the periscope, we used standard white PVC pipe with a diameter of 10 cm, a clear acrylic sheet, an oval mirror (purchased at a craft store), an adhesive, and a silicone sealer. The black target was cut to a diameter of 20 cm from a black plastic 5-gallon bucket lid and attached to a narrow PVC pipe spray painted flat black. Field measurements were made by two people whenever possible. When only one researcher was available, the measuring tape and black disk target were attached to a ten-pound kettle bell while the researcher viewed the target from the periscope and measured distance. Measurements were made approximately 20-30 cm above the river bottom by wading into the river to a depth of approximately 50-60 cm. All visibility measurements were made by the same investigator to eliminate variability due to visual acuity of the observer.

Site visits occurred after spring and summer precipitation events in 2014 and 2015, at intervals ranging from several times per day after the hydrograph peaks, to approximately once every 2-5 days as flow receded. BDV was recorded in meters as the average distance of three repeated measurements. Water samples were collected and stored at ~4° C at the lab at the University of Arkansas and processed within 48 hours. We used a Turner Designs Model 7200 Trilogy™ fluorometer fitted with a turbidity module to record the average of three rapidly consecutive measurements on each sample in nephelometric turbidity units (NTU). We filtered
water for total suspended solids (TSS; \(\text{mg L}^{-1}\)) according to standard methods \([APHA, 2005]\) using Whatman GF/F 47mm glass fiber filters and immediately dried, then weighed them. We replicated approximately 10% of TSS samples to assess measurement error.

**Statistical analyses**

Statistical analyses were executed in R \([R \text{ Core Team}, 2015]\). All measurements were \(\log_{10}\) transformed prior to analysis to account for the typical lognormal distribution of water quality data \([Hirsch et al., 1991]\), then investigated for normality by Shapiro-Wilk tests. Our critical alpha level was 0.05 for all significance tests. We first investigated the relationships among BDV, TSS, and turbidity with standard major axis regression (SMA) using the SMATR package in R \([Warton et al., 2012]\). SMA is particularly suited for estimating the functional relationship between two variables that are both subject to natural variability and measurement error \([Warton et al., 2006; Sokal and Rohlf, 2012]\). SMA fits a regression line that minimizes the residuals in both the vertical and horizontal directions \([Warton et al., 2006]\). Resulting SMA regression statistics can be applied to the linear relationship \(\log_{10} y_2 = \log_{10} y_1 \beta_1 + \beta_0\) (Eq. 3), and equations are reported herein as the back-transformation—the power law model \(y_2 = 10^{\beta_0} y_1^{\beta_1}\) (Eq. 4), where \(y_1\) and \(y_2\) are the independent and dependent variables, respectively, \(\beta_0\) is the regression intercept, and \(\beta_1\) is the regression slope. Because the SMA method minimizes the residuals in both the X and Y variables, the regression is symmetric. Here, we defined the axes of the independent and dependent variables primarily as a matter of convention. We tested for significant differences among correlation coefficients \((r)\) with Williams’ test, as recommended by Steiger \([1980]\).

To examine how the relationship between BDV and TSS in our study compared to those in previously published studies, we extracted data from graphs in those publications using Web
Plot Digitizer [Rohatgi, 2015]. We allowed the application to automatically identify data points and then manually added or adjusted them as needed. We used the extracted data to perform our own correlation analyses, and used SMA to obtain regression statistics to compare with those of our study. Using the SMATR package in R [Warton et al., 2012], we then tested whether SMA fits for the four studies shared a common slope.

Finally, because the asymmetric minimization of residuals by ordinary least squares regression (OLS) is more appropriate than SMA for prediction [Warton et al. 2006, Sokal and Rohlf 2012], we used OLS to derive predictive models of TSS and turbidity as a function of BDV. OLS allows us to estimate the most likely value of $y$ for an observed value of $x$ by fitting a model with the smallest error in the predicted variable [Legendre and Legendre, 2012]. We report these results as the back-transformation, $y = 10^{\beta_0 + \varepsilon x^{\beta_1}}$ (Eq. 5), where $\varepsilon$ is Duan’s [1983] non-parametric smearing estimate of bias [Helsel and Hirsch, 2002]. We calculated Allen’s prediction sum of squares ($PRESS$) statistic with the MPV package [Braun, 2015] in R to allow us to compare the validity of the OLS regression results. Allen’s $PRESS$ statistic is a jackknife technique that refits a regression model removing each observation from its own predicted response and compares it to the original regression. The $PRESS$ statistic is calculated by $PRESS = \sum_{i=1}^{n}(y_i - \hat{y}_i)$ (Eq. 6), where $y_i$ is the measured $i$th response, and $\hat{y}_i$ is the predicted $i$th response when the observation is removed [Allen, 1974]. A lower $PRESS$ statistic indicates a better model [Helsel and Hirsch, 2002].
Assessment

Relationships among variables

Descriptive statistics for our observations of BDV, TSS, and turbidity across the entire data set are given in Table 2. Coefficients of determination ($r^2$) indicated strong correlation among the variables (Table 3). The relationship between BDV and TSS (Figure 2 a) was the strongest of the three correlations with the least standard error of the slope, and can be described by the model $BDV = 4.3 \ TSS^{-0.71}$ (Eq. 7). BDV as a function of turbidity (Figure 2 b) had the relationship described by $BDV = 4.9 \ NTU^{-0.69}$ (Eq. 8), where $NTU$ is turbidity as measured in nephelometric turbidity units by the Turner flurometer turbidity module. Williams’ test indicated significant differences in correlation coefficients of BDV versus TSS ($r = -0.97$) and BDV versus turbidity ($r = -0.92$). Turbidity versus TSS (Figure 2 c) can be described by $NTU = 1.2 \ TSS^{1.03}$ (Eq. 9), and displayed the least correlation of the three relationships. When relationships among variables in our study were compared to those of extracted data sets from similar studies, comparison of SMA regression slopes indicated significant differences (Figure 3).

Predictive models

The strength of the correlations between BDV and TSS prompted the development of predictive models based on OLS regression of the log$_{10}$-transformed data. TSS as a function of BDV explained 94% of the variation, with a PRESS statistic of 2.10, and was described by the equation $TSS = 8.3 \ BDV^{-1.36}$ (Eq 10). However, ANCOVA determined significant interaction effects among rivers, which impelled us to model the relationships separately (Table 4). PRESS statistics suggested separate models for each river were stronger than that of the entire data set.
(Table 4). Evaluation by OLS of BDV as a predictor of turbidity ($r^2 = 0.85$) gave us the relationship $\text{NTU} = 11.5 \text{BDV}^{-1.33}$ (Eq. 11), with a PRESS statistic of 5.32 and standard error of the regression of 19%. ANCOVA of this relationship returned no significant interaction effects among rivers.

**Discussion**

Similar studies from New Zealand report strong correlations among BDV, TSS, and turbidity (Table 5). The weakest of these was found by Davies-Colley and Close [1990], in which they note high variability within and among rivers as a result of sampling under base flow conditions. The strongest correlation in our data set was that between BDV and TSS ($r = -0.97$). The only other study to determine correlations with such strength was that of Hughes et al. [2014]. The common element between these two studies is that both sampled under relatively high flow conditions. This is particularly encouraging because these are the flow conditions for which routine monitoring is generally least representative, and the ease and utility of the black disk method could allow a practical way to fill this gap in river data collections. In comparisons among the extracted data sets and ours, we found significant differences in slopes among relationships of BDV and TSS (Figure 3) to preclude the development of a broadly applicable model for the region.

*Black disk visibility as a surrogate measure*

Our study suggests that BDV may be a valuable proxy for TSS, as indicated by $r^2$ values, and may be subject to less error than using turbidity (Table 3). The significant difference between correlation coefficients of BDV *versus* TSS and BDV *versus* turbidity further supports the strength of the relationship of BDV over that of turbidity. Measurements of BDV may also
prove useful in developing rating curves estimating optical loads of clarity reducing substances, analogous to those commonly used in estimating sediment loads [Elliott et al., 2013]. However, sediment concentrations are greater nearer the river bottom, and substantial bed load transport can occur with greater flow velocities [Dodds and Whiles, 2010]. We acknowledge that our measurement of BDV at a single depth does not account for heterogeneity of sediment concentrations with depth in rivers.

To our knowledge, only one other study has approached this surrogacy concept similarly and determined BDV to be a strong predictor of TSS, though site-specific predictive models significantly reduced error [Ballantine et al. 2014]. This is particularly promising where intensive or routine monitoring is cost-prohibitive but sediment concentration dynamics are meaningful. We agree with the analysis of Ballantine et al. [2014] that a predictive model for TSS versus BDV should be localized, as we also found river dependency. Presumably, as with turbidity, this is because of variability in light attenuation by particles of different size and composition, as well as water chemistry specific to the catchment.

Differences among rivers may be related to varying concentrations of colored dissolved organic matter (CDOM), analysis of which was beyond the scope of our study. CDOM concentrations in rivers can increase following precipitation events [Julian et al., 2008], and quantity and quality of dissolved organic matter in Ozark rivers can vary with land use [Brisco and Ziegler, 2004]. Future work could investigate how CDOM might influence the relationship of BDV versus TSS among Ozark rivers (e.g., Davies-Colley et al. 2014). Because sediment and OWQ regimes in rivers may be affected by seasonality [Julian et al., 2008], we also acknowledge that our results are incomplete in that they only characterize increased flow periods during spring and summer.
Because we did not find significant interaction effects when modeling turbidity as predicted by BDV, it would be conceivable to unite the river data sets into one regression model. However, if we’ve measured BDV, we already have a valid measurement of water clarity. Considering the tenuous nature of turbidity measurements previously described, developing a predictive model of turbidity might not be wise. Indeed, the lack of interaction among rivers when BDV predicted turbidity suggests catchment-specific information was lost in this model. We’ve shown that the BDV versus TSS correlation is more explanatory with less error (Table 3), and that predicted TSS concentrations from BDV are valid for our study sites (Table 4), thus, a model of turbidity from BDV would only be useful in some very specific cases.

**Theoretical and practical considerations**

Correlative relationships were strong between variables, indicating that each measurement may be appropriate in describing OWQ in terms of the others. We do not necessarily suggest the BDV method supplant turbidity measurements in rivers. Turbidity values are abundant in historical data sets, and existing technology allows for continuous measurement in-situ, both valuable in characterizing and evaluating change in the visual clarity regime of rivers [Hughes et al., 2014]. However, our results suggest that the horizontal black disk method may be superior to turbidity measurement in some ways. Turbidity is subject to greater standard error than visual clarity [Davies-Colley and Smith, 2001], and requires specialized equipment and calibration to an arbitrary standard. Even with calibration, different optical designs of turbidimeters make for incomparable data values across studies [McCluney, 1975; Lewis et al., 2007]. In fact, several authors recommend turbidimeters be calibrated to known particulate matter concentrations and discourage using turbidity standards altogether (e.g., Davies-Colley and Smith 2001, Boss et al. 2009, Davies-Colley et al. 2014). The perception is that instrumental
measurements are more precise than those made by the “subjective” human eye. Yet, experimental findings by Blackwell (1946) applied to optical theory, described in-depth by Zaneveld and Pegau [2003], suggest otherwise. Our study results agreed with the discussion presented by Davies-Colley and Smith [2001]; we determined replicate BDV measures ($CV = 5.0\%$) to be more precise than replicate turbidity measures ($CV = 6.4\%$). However, it is important to note that a single investigator performed all of our visual measurements; we make no assumption that this finding will hold with multiple observers. To our knowledge, a systematic comparison among individual viewers of the horizontal black disk in water is yet to be reported.

The most notable benefits of measurement by the black disk method are that it requires no specialized training or costly device, and results can be communicated meaningfully and scientifically. Its strengths allow it to be employed in volunteer monitoring [Storey et al., 2016], and to enhance public awareness and involvement in water quality with programs like the North American Lake Management Society’s Secchi Dip-In (http://www.secchidipin.org). While its ease of use and broad understandability and comparability are akin to the much-appreciated Secchi disk, BDV can also be used for broader analytical applications, such as to estimate the photopic beam attenuation coefficient of the medium (Eq. 2). And, because it is measured horizontally, BDV is not sensitive to light attenuation with depth by water or the vertical distribution of planktonic organisms. Because BDV is measurable where sighting range exceeds water depth, the method is particularly useful in shallow rivers.

The buoyancy of the periscope can be somewhat cumbersome, as Steel and Neuhausser [2002] noted, and it takes some practice to become proficient, particularly during high flows. When only one investigator was available, there was the added complication (and weight) of the kettle bell with which to contend. It is not recommended that solo work be attempted during high

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flow or dangerous conditions. Other options, such as the SHMAK clarity tube [Kilroy and Biggs, 2002] might usefully be incorporated in these conditions. Twice during our study we needed to reseal the periscope. Leaks allowed cool river water to get trapped inside the tube and caused the mirror to fog between readings. While this is relatively minor maintenance, it is likely to contribute to greater error and should be attended to.

Finally, BDV relates directly to aesthetics and recreational desirability, which are of particular importance in water resources management, regional economics, and communication. Visual features are the dominant influence on human perceptions of water quality [David, 1971]. Visual water clarity serves the mental processes that influence human perceptions of water quality in the environment [West et al., 2015]. Visual water clarity relates to the perceived health of the system [Harmsworth et al., 2011], issues of safety [Smith et al., 1995], and even morality [Coughlin, 1976]. Community programs that encourage public participation in water quality parameters could benefit from measurement of BDV.

**Comments and recommendations**

We investigated relationships among BDV, turbidity, and TSS in five rivers of the southwestern Ozarks to consider how measurements of BDV might be best used for water quality assessment in rivers. Previous studies evaluating the method have supported its application (e.g., Davies-Colley and Close 1990; Steel and Neuhauser 2002; Zaneveld and Pegau 2003), but it has yet to gain traction in river monitoring in North America. This study reiterates the strength of the relationship between BDV and TSS, and shows the potential of BDV as a reliable predictor of TSS in rivers.
We encourage the adoption of the black disk visibility method in rivers where other monitoring techniques are infrequent or impractical because of cost, location, or equipment availability, and where sediment dynamics are of interest. We also advocate that it be added to existing monitoring because it offers a real value of underwater visibility that can be easily communicated and compared across time and location, and measurements can be used to estimate an inherent optical property, the beam attenuation coefficient. Because the device is low-cost and simple, it can be used by watershed partnerships, citizen scientists, and property owners to gain better understanding and characterization of rivers and streams that may not be routinely monitored, but are of concern to the public.
References


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Hughes, A. O., A. H. Elliott, R. J. Davies-Colley, and A. H. Elliott (2014), Measurement of light attenuation extends the application of suspended sediment monitoring in rivers, in *Sediment Dynamics from the Summit to the Sea*, pp. 11–14, New Orleans, LA.


R Core Team (2015), R: A language and environment for statistical computing.,


Smith, D. G., and R. J. Davies-Colley (2002), If visual water clarity is the issue, then why not measure it?, in *Advisory Committee of Water Information, National Monitoring Conference 21-23 May*, pp. 1–10.


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### Tables

**Table 1.** Land use in the watersheds of five sampled southwestern Ozark rivers [US Geological Survey, 2011], and Level III ecoregion [Woods et al., 2004]; Boston Mountains (BM), Ozark Highlands (OH).

<table>
<thead>
<tr>
<th></th>
<th>Gage #</th>
<th>% Urban</th>
<th>% Forest</th>
<th>% Agri</th>
<th>Ecoregion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffalo River</td>
<td>07056000</td>
<td>3.17</td>
<td>83.24</td>
<td>11.24</td>
<td>BM, OH</td>
</tr>
<tr>
<td>near St. Joe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illinois River</td>
<td>07195430</td>
<td>16.35</td>
<td>28.52</td>
<td>52.94</td>
<td>OH</td>
</tr>
<tr>
<td>S of Siloam Springs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kings River</td>
<td>07050500</td>
<td>4.12</td>
<td>67.46</td>
<td>25.81</td>
<td>OH</td>
</tr>
<tr>
<td>near Berryville</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mulberry River</td>
<td>07252000</td>
<td>3.19</td>
<td>90.67</td>
<td>4.70</td>
<td>BM</td>
</tr>
<tr>
<td>near Mulberry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>War Eagle Creek</td>
<td>07049000</td>
<td>4.55</td>
<td>57.97</td>
<td>35.08</td>
<td>OH</td>
</tr>
<tr>
<td>near Hindsville</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Table 2. Descriptive statistics for parameters measured in five southwestern Ozark rivers.

<table>
<thead>
<tr>
<th></th>
<th>Black disk visibility (m)</th>
<th>Total suspended solids (mg L(^{-1}))</th>
<th>Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.85</td>
<td>9.63</td>
<td>16.70</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>0.75</td>
<td>11.59</td>
<td>15.03</td>
</tr>
<tr>
<td>Multiplicative standard deviation</td>
<td>2.18</td>
<td>2.98</td>
<td>3.09</td>
</tr>
<tr>
<td>Range</td>
<td>0.10 – 3.70</td>
<td>0.60 – 307.70</td>
<td>0.25 – 221.13</td>
</tr>
<tr>
<td>Mean coefficient of variation (%)</td>
<td>5.00</td>
<td>6.39</td>
<td>10.23</td>
</tr>
</tbody>
</table>
**Table 3.** Standardized major axis regression results among log$_{10}$ black disk visibility (BDV; m), log$_{10}$ turbidity, and log$_{10}$ total suspended solids (TSS; mg L$^{-1}$).

<table>
<thead>
<tr>
<th></th>
<th>BDV vs. TSS</th>
<th>BDV vs. Turbidity</th>
<th>Turbidity vs. TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept ($\beta_0$)</td>
<td>0.63</td>
<td>0.69</td>
<td>0.08</td>
</tr>
<tr>
<td>Slope ($\beta_1$)</td>
<td>-0.71</td>
<td>-0.69</td>
<td>1.03</td>
</tr>
<tr>
<td>Standard error of the slope</td>
<td>0.015</td>
<td>0.022</td>
<td>0.036</td>
</tr>
<tr>
<td>Coefficient of determination ($r^2$)</td>
<td>0.94</td>
<td>0.85</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Table 4. Combined and river-specific ordinary least squares regression results for total suspended solids (TSS; mg L\(^{-1}\)) predicted by black disk visibility (BDV; m).

<table>
<thead>
<tr>
<th></th>
<th>(r^2)</th>
<th>Std. error of regression</th>
<th>PRESS statistic</th>
<th>Power law model</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rivers</td>
<td>0.94</td>
<td>0.12</td>
<td>2.10</td>
<td>(8.3BDV^{1.36})</td>
</tr>
<tr>
<td>Buffalo R.</td>
<td>0.93</td>
<td>0.12</td>
<td>0.44</td>
<td>(8.2BDV^{1.26})</td>
</tr>
<tr>
<td>Illinois R.</td>
<td>0.95</td>
<td>0.10</td>
<td>0.35</td>
<td>(8.8BDV^{1.44})</td>
</tr>
<tr>
<td>Kings R.</td>
<td>0.94</td>
<td>0.12</td>
<td>0.42</td>
<td>(7.4BDV^{1.58})</td>
</tr>
<tr>
<td>Mulberry R.</td>
<td>0.91</td>
<td>0.08</td>
<td>0.15</td>
<td>(7.3BDV^{1.11})</td>
</tr>
<tr>
<td>War Eagle Cr.</td>
<td>0.94</td>
<td>0.12</td>
<td>0.51</td>
<td>(8.8BDV^{1.27})</td>
</tr>
</tbody>
</table>
Table 5. Correlation coefficients ($r$) of similar comparisons reported in the literature.

<table>
<thead>
<tr>
<th>Study</th>
<th>BDV vs. TSS</th>
<th>BDV vs. turbidity</th>
<th>turbidity vs. TSS</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davies-Colley &amp; Close 1990</td>
<td>-0.77</td>
<td>-0.88</td>
<td>0.69</td>
<td>97</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smith et al. 1997</td>
<td>NA</td>
<td>-0.97</td>
<td>NA</td>
<td>64</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Davies-Colley &amp; Smith 2001</td>
<td>-0.93</td>
<td>-0.92</td>
<td>0.95</td>
<td>34</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel &amp; Neuhauser 2002</td>
<td>NA</td>
<td>-0.86</td>
<td>NA</td>
<td>10</td>
</tr>
<tr>
<td>(Washington, US)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Davies-Colley et al. 2014</td>
<td>-0.92</td>
<td>-0.95</td>
<td>0.89</td>
<td>924</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hughes et al. 2014</td>
<td>-0.97</td>
<td>-0.99</td>
<td>0.97</td>
<td>8-158</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>-0.97</td>
<td>-0.92</td>
<td>0.91</td>
<td>145</td>
</tr>
<tr>
<td>(Arkansas, US)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NAs are where sediment concentrations were not reported.

1 Authors measured suspended sediment concentration rather than total suspended sediment; we assumed negligible differences.

2 Correlation coefficient was calculated here as the average of the square roots of reported $r^2$ for all sites.
Table 6. Standardized major axis regression statistics of \( \log_{10} \) black disk visibility (m) versus \( \log_{10} \) total suspended solids (mg L\(^{-1}\)) reported in the literature.

<table>
<thead>
<tr>
<th>Study</th>
<th>Intercept (( \beta_0 ))</th>
<th>Slope (( \beta_1 ))</th>
<th>Std. error of slope</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study (Arkansas, US)</td>
<td>0.63</td>
<td>-0.71</td>
<td>0.015</td>
<td>0.94</td>
</tr>
<tr>
<td>Davies-Colley &amp; Close 1990(^1,2)</td>
<td>0.65</td>
<td>-0.72</td>
<td>0.023</td>
<td>0.60</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Davies-Colley et al. 2014(^1,2)</td>
<td>0.69</td>
<td>-0.77</td>
<td>0.012</td>
<td>0.84</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hughes et al. 2014(^2)</td>
<td>0.68</td>
<td>-0.90</td>
<td>0.022</td>
<td>0.96</td>
</tr>
<tr>
<td>(New Zealand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Authors measured suspended sediment concentration rather than total suspended sediment; we assumed negligible differences.

\(^2\) Values are estimated from data extracted from published plots.
Figures

**Figure 1.** Horizontal black disk visibility device of Davies-Colley 1988 (image adapted from West et al. 2015), and photograph of target as viewed through the periscope (inset).
**Figure 2.** Mutual relationships among black disk visibility (BDV; m), turbidity (NTU), and total suspended solids (TSS; mg L\(^{-1}\)) determined by standardized major axis regression.
Figure 3. Standardized major axis regression results for relationships between black disk visibility (BDV; m) and total suspended solids (TSS; mg L\(^{-1}\)) from a. this study, b. Davies-Colley and Close 1990, c. Davies-Colley et al. 2014, d. Hughes et al. 2014, and e. all four studies.
IV. Optical water quality and particulate matter concentrations as flow recedes:

A Study of Five Rivers of the Ozarks
Abstract

Understanding optical water quality and particulate matter dynamics in recreational rivers is integral in shaping management strategies that maintain ecosystem health, perceived value and appeal, and regional economic significance in a changing environment. Suspended sediment strongly governs optical water quality and is ecologically, as well as aesthetically significant. Increased sedimentation is among the most widespread concerns in rivers throughout the world and a dominant portion of sediment transport occurs in response to increased flow. Thus, it is important to characterize particulate matter concentrations in rivers under changing flow conditions. This study sought to describe optical water quality and particulate concentration dynamics as flow recedes after precipitation events in five ecologically and recreationally significant rivers of the southwestern Ozarks. We found that relationships between particulate concentrations and the hydrograph were dependent upon catchment characteristics and discrete events were highly variable. We determined optical water quality measures to be strongly correlated to particulate matter concentrations, and may be well suited for describing variability during event flow in the absence of more intensive monitoring programs.
Introduction

Increased sedimentation is among the most widespread pollutant concerns in US rivers, and is the primary cause of impairment in Arkansas rivers and streams [US EPA, 2008]. Suspended sediment in rivers is greatly influenced by land use within the watershed, and can transport adsorbed pollutants downstream [Dodds and Whiles, 2010]. Settling of suspended solids can affect benthic organisms and may alter the structure and productivity of the biotic community [Ryan, 1991]. Suspended sediment concentrations (SS) in rivers are often strongly related to discharge (Q), and sediment rating curves are most commonly developed with the power function, $SS = aQ^b$, where coefficients, $a$ and $b$, are empirically derived by ordinary least squares regression analysis of the log-transformed variables [Horowitz, 2003]. However, the power function can underestimate high sediment concentrations and overestimate low concentrations [Horowitz, 2003], and requires a correction factor to account for bias upon back-transformation [e.g., Duan, 1983; Miller, 1984; Ferguson, 1986]. Importantly, a significant proportion of annual sediment transport can occur during only a few storm events, which may or may not be included in routine measurements. For example, up to 95% of annual sediment transport in North American rivers can occur during flows constituting only 10% of the year [Meade et al., 1990]. The exact relationship of suspended sediment concentration with discharge can vary based on sediment availability, precipitation intensity, distance of sediment source, seasonality [Williams, 1989], shear strength and sediment cohesiveness [Ji, 2008], and catchment soil type [Sander et al., 2011]. Thus, the accuracy of sediment rating curves can depend on the calibration data set [Thomas, 1988; Horowitz, 2003], and rating curves can be severely inadequate when developed under infrequent sampling [Walling, 1977; Kronvang et al., 1997].
The precise relationship between suspended sediment and discharge frequently varies based on whether flow is rising or receding [Klein, 1984; Glysson, 1987; Eder et al., 2010] and is often better expressed in consideration of a hysteresis loop [Sander et al., 2011]. The shape and direction of the hysteresis loop can be a result of multifaceted interactions between excess overland flow, physical soil characteristics, antecedent sediment mobilization and deposition, particle size distribution [Sander et al., 2011; Landers and Sturm, 2013], and sediment source area [Klein, 1984; Williams, 1989; Seeger et al., 2004]. Accurately characterizing hysteresis in sediment concentrations and transport in individual rivers often requires costly, time-consuming, and intensive, long-term monitoring, and is arguably impractical in many cases. A few studies have investigated physicochemical characteristics in relation to flow in Ozark rivers. For example, Petersen et al. [2000] determined that 50% of stream flow in Buffalo River occurred during only 8% of their study period, and further concluded greater than 90% of annual nutrient and sediment loads were contributed during surface runoff conditions. Davis and Bell [1998] recognized hysteresis in total phosphorus with flow in rivers of the Ozarks as an effect of variation in sediment mobilization along the hydrograph. Haggard et al. [2003] noted likely hysteresis effects in total phosphorus concentrations in Illinois River, and stressed the importance of targeting storm events when developing regression models. However, studies detailing particulate dynamics in rivers of the central United States are relatively sparse [Brown and Matthews, 2006].

Optical water quality (OWQ) is defined as the suitability of water for its role in the environment as governed by its composition and the geometric structure of the light field [Tyler, 1978; Kirk, 1988]. Because it involves the behavior of light in both the visible and photosynthetically available part of the electromagnetic spectrum, OWQ is relevant to water
resources management [Julian et al., 2013]. OWQ can affect water temperature, fish predation, predator evasion, photosynthesis, and many other biogeochemical reactions [Wetzel, 1975; Kirk, 2011]. Suspended particulate matter is often the dominant influence on OWQ in rivers [Davies-Colley and Close, 1990; Davies-Colley and Smith, 2001; Julian et al., 2008]. Inorganic and organic particulates influence OWQ differently based on size, shape, and composition [Davies-Colley et al., 1993; Gippel, 1995], and inorganic clay particles can carry substantial amounts of adsorbed organic matter [Brown and Matthews, 2006]. Although light availability is a fundamental factor in river ecology, few studies exist that characterize US rivers in terms of OWQ [Julian et al., 2008].

We undertook this study seeking to characterize variability in suspended particulate matter and OWQ as flow recedes after precipitation events in five ecologically and recreationally significant rivers of the southwestern Ozarks in Arkansas, US. We also sought to investigate how the organic proportion of particulate matter is related to specific aspects of the hydrograph. Our measured water quality (WQ) variables were chosen to allow us to test the following hypotheses (Figure 1):

1. Because particulate matter concentrations in rivers are sensitive to many environmental influences, precise relationships between particulate matter concentrations and discharge will be event specific.
2. Because of diminishing carrying capacity for heavier inorganic sediments and more favorable conditions for sestonic organisms, the organic proportion of suspended sediment will increase with time after the event peak.
3. Because OWQ is strongly governed by scattering by suspended particulates, measurements of horizontal black disk visibility and particulate matter concentrations
will respond similarly to events, and may serve to generally describe the dynamics as flow recedes in rivers, in the absence of more intensive water quality measurements.

**Materials and Methods**

*Study Sites and data collection*

We chose five popular recreational rivers in the southwestern Ozark for this study. The sample location on each river coincided with a US Geological Survey gage measuring discharge (Q) at 15-minute intervals (gage numbers are given in Table 1). All five rivers originate in the Boston Mountains Plateau and are generally characteristic of the region’s rivers. The Arkansas Department of Environmental Quality designates the Buffalo (BUF), Kings (KIN), and Mulberry (MUL) Rivers as Extraordinary Resource Waters; BUF and MUL are Natural and Scenic Waterways; the Illinois River (ILL) is designated Ecologically Sensitive. BUF, ILL and War Eagle Creek (WAR) primarily cut into the Boone Formation, a Mississippian cherty limestone of the Springfield Plateau. BUF, with the largest drainage area of the five rivers in this study (Table 1), drains areas of the Ozark Highlands (OH) and Boston Mountains (BM) ecoregions and meets the White River. ILL, WAR, and KIN are primarily in the Ozark Highlands ecoregion. KIN and WAR flow northward to the White river; however, only the Kings cuts into the Ordovician Dolomites of the Salem Plateau. ILL flows north then west into Oklahoma, and southward, eventually reaching the Arkansas River. MUL flows southward through the Pennsylvanian sandstones and shales of the Boston Mountains Plateau to the Arkansas River. Land use in the region varies, but is predominantly forested and agricultural, most of which is in pasture (Table 1).
This study took place between March and October in 2014 and 2015. Site visits were initiated by precipitation events and occurred at intervals of approximately once every 1 to 3 days as flow receded. After preliminary analyses of samples collected in 2014, we shifted the sampling interval to focus more intensive sampling on fewer individual events. For each sampling event, we calculated the average of three consecutive in-situ black disk visibility measurements [Davies-Colley, 1988b] (BDV). We collected grab samples, transported them on ice, and stored them at ~4°C at the lab at the University of Arkansas, where they were processed within 48 hours. We filtered up to 1L of water through Whatman GF/F 47 mm glass fiber filters for analysis of total suspended solids concentration (TSS) [APHA, 2005]. We filtered samples through Whatman GF/F 25 mm glass fiber filters for analysis of suspended chlorophyll a (Schl) and particulate nitrogen (PN) concentrations. We used a Turner Designs Model 7200 Trilogy™ fluorometer fitted with an absorbance module to measure Schl by the acid digestion method following overnight extraction with acetone [APHA, 2005]. We used a Thermo Scientific™ Flash 2000 Organic Elemental Analyzer to measure PN [APHA, 2005].

Statistical Analyses

All data were log_{10} transformed to account for the tendency for log-normal distributions in water quality data [Hirsch et al., 1991], with the exception of proportion data, which were logit transformed as recommended by Warton and Hui [2011]. All statistical tests were performed on the transformed data with a critical alpha level of 0.05. We tested each WQ variable for equality of variance among the rivers with Levene’s test and performed an omnibus one-way analysis of variance (ANOVA) to determine whether differences in means of measured parameters existed among the rivers. Upon detection of significant differences in those
parameters with equal variance among rivers, we performed multiple comparisons using Tukey’s honestly significant difference (HSD) test in the “stats” package in R [R Core Team, 2015], which automatically adjusts for unequal sample sizes. Parameters for which we determine unequal variance among rivers, we used the Games-Howell method to test pairwise differences because it is less sensitive to variance inequalities [Games and Howell, 1976]. We manually identified the peak of each flow event and calculated the length of time after the hydrograph peak (TAP) for each sample.

We critically analyzed relationships between particulate concentrations and Q/TAP using Pearson’s correlation coefficient and ordinary least squares regression (OLS). We further examined differences in regression relationships among select well-represented events to compare event-specific dynamics within rivers using OLS and analysis of covariance (ANCOVA). We assumed the inorganic contribution to PN was negligible [following Beusen et al., 2005] because PN is greatly dominated by proteins, amino acids, and nucleic acids [Meybeck, 1982; Dodds and Whiles, 2010], and is well correlated to particulate organic carbon at TSS concentrations of our study [Ittekkot and Zhang, 1989]. Therefore, we examined OLS regressions of the ratio of PN to TSS versus TAP to investigate changes in the relative organic content of TSS as flow receded.

Results

Differences among five rivers

Summary statistics for each measured variable are shown in Table 2. Analyses of variance indicated significant differences (p < 0.05) among rivers in means for every measured WQ variable. Pairwise comparisons indicated mean values of log-transformed instantaneous Q
were not statistically different for four of the five rivers; WAR was generally measured at lower discharge (Figure 2a). Pairwise comparisons for WQ variables showed that ILL and BUF were significantly different from one another for all measured variables (Figure 2b-e). KIN, MUL, and WAR shared statistical similarities with BUF and/or ILL in means of log-transformed values of BDV (Figure 2b). The means of log-transformed TSS and PN for ILL were statistically different from all four of the other rivers (Figure 2c &e). The mean of log-transformed Schl for MUL was statistically less than that of the other four rivers (Figure 2d).

The ratio of PN to TSS was significantly and positively correlated with TAP in BUF, ILL, and KIN, indicating that suspended particulates were more dominated by organic matter with as flow receded. Regressions in MUL and WAR indicated slopes were not significantly different from zero (Figure 3), suggesting no relationship between organic proportion of suspended particulate matter with TAP. ANCOVA of PN:TSS versus TAP only returned significant interaction effects among events in MUL.

**Buffalo River**

For the complete period of data collection, none of our measured WQ variables were significantly correlated with Q (Table 4). However, WQ variables were significantly correlated with TAP, with the exception of Schl. We chose three well-represented events on BUF to compare with one another (Figure 4). ANCOVA of the relationship of each WQ variable with Q resulted in significant interaction effects among events (denoted with asterisks Table 4) for BDV (Figure 4b) and PN (Figure 4e). Though interaction effects with TSS were only significant at the 90% level, rather than at our predetermined alpha (Figure 4c), scrutiny of scatter plots and OLS regressions revealed notable variation among events. When relationships between the WQ
variables and TAP were analyzed with ANCOVA, we also determined interaction effects for BDV and PN, but not for TSS and Schl.

**Illinois River**

Particulate concentrations were strongly correlated with Q (Figure 5) and TAP in ILL (Table 3). ANCOVA of each of the WQ variables with Q on six well-represented events only resulted in significant interaction effects for Schl (Figure 5d), indicating Q was a relatively reliable predictor of particulate concentrations across events (Figure 5b, c, & e). ANCOVA of TAP relationships only determined interaction effects among discrete events for TSS.

**Kings River**

Correlations between each WQ variable and Q (Figure 6) and TAP in KIN were moderate to strong, and all were significant (Table 3). ANCOVA of relationships between Q and measured variables showed significant interaction effects (denoted with asterisks in Table 3) for TSS and PN (Figure 6c & e). Schl was the only WQ variable for which we did not determine interaction effects among discrete events in relationships with TAP.

**Mulberry River**

Discharge in MUL (Figure 7) was significantly, though relatively weakly, correlated with BDV and TSS and not significantly correlated with Schl and PN (Table 3). TAP was significantly correlated with each WQ variable and was generally a strong predictor of particulate concentrations. ANCOVA of the relationships between each WQ variable and Q and
TAP did not return any significant interaction effects among three well-sampled events (Figure 7).

*War Eagle Creek*

Discharge generally described much of the variation in WQ variables in WAR (Figure 8), except in the case of Schl, for which correlation was not significant (Table 3). Measured variables were significantly, but less strongly correlated with TAP. ANCOVA only resulted in significant interaction effects among events for the relationship between BDV and Q (Figure 8a), and no interaction effects were observed in relationships with TAP.

**Discussion**

*Water quality relationships with event flow*

Water quality variables in BUF and MUL were either weakly or not significantly correlated with discharge over the complete study period. In discrete events, the intuitive relationship of increased particulate matter with increased discharge was much more evident in BUF. Interaction effects in BUF indicated the magnitude of response in BDV and PN were dependent upon the specific hydrograph event. However, the lack of significant interactions among discrete events in MUL (Figure 7) may be because WQ measures were generally less variable than in BUF. While both rivers are dominated by forested land, the difference between BUF and MUL was likely related to other catchment characteristics. The MUL watershed exists fully within the Boston Mountains ecoregion, and the steeper gradient underlain by sandstone means event flow is likely more dominated by overland flow, with little groundwater-surface water interaction [Adamski et al., 1995]. Whereas, while the headwaters of BUF are in the
Boston Mountains ecoregion, the Ozark Highland ecoregion dominates the BUF watershed, and the karst geology promotes substantial groundwater contributions to flow [Adamski et al., 1995], effectively diluting the storm response.

Alternately, in ILL, KIN, and WAR, discharge was relatively strongly correlated with WQ variables, except Schl in WAR. Interaction effects among well-sampled events were more common in KIN (Figure 5) than in ILL and WAR. It appeared that variability in event magnitudes and antecedent conditions of discrete events in ILL and WAR did not influence relationships between particulate concentrations and discharge as strongly as they did in KIN. Agricultural and urban land use are dominant contributors to excessive nutrient concentrations in surface waters [Carpenter et al., 1998], and agriculture is a principle source of sediment pollution in the US [Waters, 1995]. We suspect our observations in ILL are likely a result of a drainage area in nearly 70% agricultural and urban land use, with point and nonpoint source nutrient pollution [Green and Haggard, 2001]. WAR has the second greatest agricultural land use (35%) of the rivers in our study, and the second highest geometric mean concentrations of TSS, Schl, and PN (Figure 2; Table 2). It is reasonable to suggest our results in ILL and WAR are characteristics of their watersheds, as they are less prone to natural temperance provided by the forested landscape, i.e., sediment storage and release thresholds [Walling, 1999] and riparian nutrient uptake [Peterjohn and Correll, 1984]. Our observations in these five rivers suggest as the watershed is more influenced by agricultural practices in the Ozarks, particulate concentrations may be more tightly coupled to event discharge. Particulate concentrations in ILL and WAR may be more adequately predicted by simple power law equations with sufficient development targeting hydrograph events than in BUF, KIN, and MUL. The event-specific relationships we hypothesized were generally only observed in BUF and KIN.
Organic proportions of suspended sediment

The ratio of PN to TSS was significantly and positively correlated with TAP in BUF, ILL, and KIN (Figure 3), implying organic matter made up a greater proportion of TSS as flow receded, as we predicted. However, even though reduced velocity and increased clarity as flow receded may have offered more favorable conditions for sestonic algae proliferation, we observed declining concentrations of Schl as flow receded. We suggest sloughing of periphyton from upstream during high flow obscured our ability to observe whether an increase in sestonic primary productivity contributed to PN:TSS. ANCOVA of the relationship of PN:TSS with TAP only resulted in significant interaction effects among events for MUL, suggesting the slope of this relationship is not event-specific in the other four rivers. In MUL, PN:TSS was not significantly correlated with TAP. However, we necessarily omitted six PN results from the MUL data set due to laboratory error, representing 30% of our MUL observations and the entirety of one of the three discrete events, which severely limited this data set. The slope of PN:TSS versus TAP in WAR was not significantly different than zero and the relationship demonstrated substantial scatter, yet the lack of a significant interaction effects indicated no better explanation based on single events. Here again we omitted four PN results, representing one of the five events in WAR. The lack of a significant slope in WAR suggests the organic proportion of suspended sediment was relatively stable over the first several days after precipitation events.

Geometric means of Schl concentrations were generally low (less than 1.5 µg/L, except in ILL), which is characteristic of streams in the Ozark region [Haggard et al., 2007; Maret et al., 2010]. The geometric mean concentration of Schl in MUL was significantly less than that of the other four rivers (Figure 1e). BDV and TSS in MUL were less variable and Schl was lower than
in any of the other rivers (Table 2), suggesting there may be consistently less light availability for photosynthesis in MUL than in the other four rivers. The MUL watershed is largely undeveloped, with a higher flow gradient, and lies within a different ecoregion than the other four rivers (Table 1). These physical features, alongside the slightly negative, though not statistically significant, correlation of Schl with discharge and the strong negative correlation with TAP, suggested flushing of sestonic algae downstream in MUL.

During increased flow in rivers, Schl concentrations may increase due to scouring of the benthos, which can be affected by both flow magnitude and pre-event periphyton biomass [Biggs and Close, 1989; Lohman and Jones, 1999]. KIN and ILL were the only two sites for which we determined significant correlations between Schl and discharge. While geometric mean PN concentrations were significantly different between the two rivers, PN was highly variable in KIN, with the greatest (and lowest) measured concentrations of our study (Figure 1f & g), perhaps indicating overall more nutrient availability for periphyton growth. Because KIN and ILL are relatively similar in size and sampled discharge, we postulate that benthic periphyton upstream may have been in sufficient quantity to be sloughed off and suspended with increased water velocity. Whereas in WAR, everything except Schl was correlated with discharge, perhaps indicating a near balance between dilution and flushing of sestonic algae and suspension of sloughed periphyton. Our study was limited to approximately the first eight days after each event peak. The hypothesized overtaking of suspended matter by primary productivity in rivers may occur further along the hydrograph, as the rivers return to baseflow conditions. Future work could seek to identify the period where event dynamics shift toward baseline characteristics in rivers of the Ozarks.
Optical water quality

Measurements of OWQ can be an effective, affordable method for characterizing sediment concentrations in rivers [Davies-Colley et al., 2014], and the behavior of light in the aquatic system is, in itself, often the component of interest [Davies-Colley, 1988b; Smith and Davies-Colley, 2002]. BDV may be a viable surrogate for TSS when developed with localized models [Ballantine et al., 2014]. Our results suggest that OWQ measurements may be valuable in characterizing receding flow dynamics in the absence of resources supporting more precise chemical and physical characterization. However, because we did not observe patterns of event-specific control in BDV relationships analogous to those of particulate matter concentrations (as assessed by ANCOVA), BDV may not demonstrate similar sensitivities as concentration measurements as flow recedes in Ozark rivers. Though perhaps not generally a strong control, colored dissolved organic matter can influence BDV, especially following precipitation events [Julian et al., 2008]. Characteristics of dissolved organic matter in the Ozarks can also vary with land use [Brisco and Ziegler, 2004]. We propose, when general characteristics of particulate matter concentrations as flow recedes in rivers of the Ozarks are sufficient, BDV can be an inexpensive and adequate tool. Nevertheless, more research is needed to determine sensitivities of simple optical methods to particle size distributions, organic proportions, and dissolved components in rivers before considering them for detailed characterizations.

This study helps to describe variability in OWQ in five recreational rivers of the Ozarks in Arkansas. Outdoor recreation in Arkansas generates approximately $10 billion in consumer spending each year [Outdoor Industry Association, 2012]. Visitors to the Buffalo National River alone spent over $56 million in 2014 [National Park Service, 2015]. OWQ is particularly relevant in human perceptions of water quality [Smith et al., 1995a; House and Fordham, 1997;
West et al., 2015] and judgments of suitability for recreation [Egan et al., 2009; Smith et al., 2015]. Given the popularity of kayaking and canoeing in the Ozarks, many recreationalists will be likely to experience the rivers during periods of increased flow, thus offering a social application for the increased frequency of water quality assessment that may be facilitated using OWQ methods. We acknowledge, however, that recreational visitation also occurs during lower flow conditions, especially in summer. Our study was limited to approximately the first eight days after peak flow. Future work could extend this time period to characterize sediment concentration and OWQ dynamics as event flow shifts to base flow conditions in recreational rivers of the Ozarks.

Conclusions

A better understanding of particulate dynamics and their influence on OWQ may be valuable to water resources management in recreational rivers of the US. Our study showed that particulate matter concentrations in rivers in the southwestern Ozarks are temporally variable, and precise relationships with the hydrograph can differ based upon catchment characteristics, and among specific events within the same catchment. This study also demonstrated the relatively weak relationship of particulate matter concentrations with discharge in less-disturbed rivers, and more predictable relationships in agricultural watersheds. Because OWQ measurements can be useful for characterizing general particulate matter dynamics, we suggest they be considered for more frequent monitoring in scenic and ecologically sensitive rivers as climate and land use changes continue to take effect in the region.
References


Davies-Colley, R. J., D. J. Ballantine, S. H. Elliott, A. Swales, A. O. Hughes, and M. P. Gall (2014), Light attenuation - a more effective basis for the management of fine suspended


R Core Team (2015), R: A language and environment for statistical computing.,


Smith, D. G., and R. J. Davies-Colley (2002), If visual water clarity is the issue, then why not


## Tables

### Table 1. Catchment characteristics of study rivers; land use from *US Geological Survey* [2011], and Level III ecoregion from *Woods et al.*, [2004]; BM, Boston Mountains; OH, Ozark Highlands

<table>
<thead>
<tr>
<th>Gage #</th>
<th>Area (km²)</th>
<th>Urban (%)</th>
<th>Forest (%)</th>
<th>Agriculture (%)</th>
<th>Ecoregion</th>
</tr>
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<tr>
<td>Buffalo R. 07056000</td>
<td>2147</td>
<td>3.2</td>
<td>83.2</td>
<td>11.2</td>
<td>BM, OH</td>
</tr>
<tr>
<td>Illinois R. 07195430</td>
<td>1489</td>
<td>16.4</td>
<td>28.5</td>
<td>52.9</td>
<td>OH</td>
</tr>
<tr>
<td>Kings R. 07050500</td>
<td>1365</td>
<td>4.1</td>
<td>67.5</td>
<td>25.8</td>
<td>OH</td>
</tr>
<tr>
<td>Mulberry R. 07252000</td>
<td>966</td>
<td>3.2</td>
<td>90.7</td>
<td>4.7</td>
<td>BM</td>
</tr>
<tr>
<td>War Eagle Cr. 07049000</td>
<td>681</td>
<td>4.6</td>
<td>58.0</td>
<td>35.1</td>
<td>OH</td>
</tr>
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Table 2. Geometric mean and (multiplicative standard deviation) for measured water quality variables

<table>
<thead>
<tr>
<th></th>
<th>BDV (m)</th>
<th>TSS (mg/L)</th>
<th>Schl (µg/L)</th>
<th>PN (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffalo R.</td>
<td>1.01 (2.22)</td>
<td>7.79 (2.75)</td>
<td>1.14 (1.94)</td>
<td>0.09 (1.91)</td>
</tr>
<tr>
<td>Illinois R.</td>
<td>0.42 (1.78)</td>
<td>33.48 (2.51)</td>
<td>2.70 (2.84)</td>
<td>0.22 (2.04)</td>
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<tr>
<td>Kings R.</td>
<td>0.90 (2.09)</td>
<td>9.99 (3.85)</td>
<td>1.43 (2.31)</td>
<td>0.11 (2.50)</td>
</tr>
<tr>
<td>Mulberry R.</td>
<td>0.71 (1.63)</td>
<td>10.81 (1.72)</td>
<td>0.46 (1.96)</td>
<td>0.09 (1.54)</td>
</tr>
<tr>
<td>War Eagle Cr.</td>
<td>0.61 (2.15)</td>
<td>15.78 (2.73)</td>
<td>1.38 (1.84)</td>
<td>0.13 (1.81)</td>
</tr>
</tbody>
</table>
Table 3. Correlation coefficients for relationships among measured variables and discharge (Q; m$^3$/s) and time after event peak (TAP; d); text in bold indicates regression slope was significantly different from zero (p < 0.05); asterisk indicates ANCOVA returned significant interactions among discrete hydrograph events.

<table>
<thead>
<tr>
<th></th>
<th>BDV (m)</th>
<th>TSS (mg/L)</th>
<th>Schl (µg/L)</th>
<th>PN (mg/L)</th>
<th>PN:TSS</th>
</tr>
</thead>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>Q</td>
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<td>0.01</td>
<td>0.04*</td>
<td>-0.30</td>
</tr>
<tr>
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<td>-0.77</td>
<td>-0.22</td>
<td>-0.79*</td>
<td><strong>0.57</strong></td>
</tr>
<tr>
<td><strong>Illinois R.</strong></td>
<td></td>
<td></td>
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</tr>
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<td>Q</td>
<td>-0.84</td>
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<td><strong>0.68</strong>*</td>
<td>0.87</td>
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<td>-0.69</td>
<td>-0.72</td>
<td>0.49</td>
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<td><strong>Kings R.</strong></td>
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</tr>
<tr>
<td>Q</td>
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<td>0.66</td>
<td>0.67*</td>
<td>-0.80*</td>
</tr>
<tr>
<td>TAP</td>
<td><strong>0.72</strong>*</td>
<td>-0.78*</td>
<td>-0.72</td>
<td>-0.69*</td>
<td><strong>0.79</strong></td>
</tr>
<tr>
<td><strong>Mulberry R.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>-0.51</td>
<td><strong>0.48</strong></td>
<td>-0.37</td>
<td>0.09</td>
<td>-0.68*</td>
</tr>
<tr>
<td>TAP</td>
<td><strong>0.80</strong></td>
<td>-0.70</td>
<td>-0.72</td>
<td>-0.90</td>
<td>-0.06*</td>
</tr>
<tr>
<td><strong>War Eagle Cr.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Q</td>
<td>-0.81*</td>
<td><strong>0.81</strong></td>
<td>0.19</td>
<td><strong>0.66</strong></td>
<td>-0.65</td>
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<tr>
<td>TAP</td>
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<td>-0.51</td>
<td>-0.43</td>
<td>-0.57</td>
<td>0.14</td>
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Figure 1. Hypothesized model of relationships of suspended particulate matter and optical water quality as flow recedes in individual hydrograph events
Figure 2. Boxplots of log\textsubscript{10} transformed variables; a) discharge (m\textsuperscript{3}/L); b) black disk visibility (m); c) total suspended solids (mg/L), d) suspended chlorophyll \( \mu \text{g/L} \); e) particulate nitrogen (mg/L); letter above boxes indicate statistical differences in pairwise comparisons (p < 0.05)
**Figure 3.** Ordinary least squares regression results for logit transformed PN:TSS versus $\log_{10}$ transformed time after hydrograph peak, dashed line indicates regression slope was not significant different than zero; a) Buffalo River; b) Illinois River; c) Kings River; d) Mulberry River; e) War Eagle Creek
Figure 4. Buffalo River hydrograph (a) and ordinary least squares regression results of $\log_{10}$ transformed water quality variables *versus* $\log_{10}$ transformed discharge (m$^3$/s); b) black disk visibility (m); c) total suspended solids (mg/L); d) suspended chlorophyll-$a$ (µg/L); e) particulate nitrogen (mg/L); multiple lines demonstrate event-specific regression results when ANCOVA determined significant interaction effects; dashed lines indicate the regression slope was not significantly different from zero.
Figure 5. Illinois River hydrograph (a) and ordinary least squares regression results of log_{10} transformed water quality variables versus log_{10} transformed discharge (m^3/s); b) black disk visibility (m); c) total suspended solids (mg/L); d) suspended chlorophyll-a (µg/L); e) particulate nitrogen (mg/L); multiple lines demonstrate event-specific regression results when ANCOVA determined significant interaction effects; dashed lines indicate the regression slope was not significantly different from zero.
**Figure 6.** Kings River hydrograph (a) and ordinary least squares regression results of $\log_{10}$ transformed water quality variables *versus* $\log_{10}$ transformed discharge (m$^3$/s); b) black disk visibility (m); c) total suspended solids (mg/L); d) suspended chlorophyll-$a$ (µg/L); e) particulate nitrogen (mg/L); multiple lines demonstrate event-specific regression results when ANCOVA determined significant interaction effects; dashed lines indicate the regression slope was not significantly different from zero.
Figure 7. Mulberry River hydrograph (a) and ordinary least squares regression results of log$_{10}$ transformed water quality variables versus log$_{10}$ transformed discharge ($m^3/s$); b) black disk visibility (m); c) total suspended solids (mg/L); d) suspended chlorophyll-a ($\mu g/L$); e) particulate nitrogen (mg/L); dashed lines indicate the regression slope was not significantly different from zero
Figure 8. War Eagle Creek hydrograph (a) and ordinary least squares regression results of log_{10} transformed water quality variables \textit{versus} log_{10} transformed discharge (m^3/s); b) black disk visibility (m); c) total suspended solids (mg/L); d) suspended chlorophyll-a (µg/L); e) particulate nitrogen (mg/L); multiple lines demonstrate event-specific regression results when ANCOVA determined significant interaction effects; dashed lines indicate the regression slope was not significantly different from zero.
V. Optical Water Quality and Human Perceptions of Rivers: An Ethnohydrology Study

This chapter has been accepted as:

Abstract

Rivers are revered worldwide for their ecologic, scenic, and recreational value. The capacity to communicate effectively among human groups with vested interest in rivers hinges on understanding the nature of human perceptions of water quality and the extent to which they vary intra-culturally. Recognizing the intersection between measured water quality and the characteristics of rivers that influence human perceptions facilitates potential for better communication across disciplines and among stakeholders. We conducted interviews and a pile-sort task with water quality experts and non-experts. Our analysis suggested human evaluation of water quality is guided by culturally-constructed criteria, regardless of respondent expertise, experience, or demographics. Cluster analysis results implied that measured physical and chemical parameters of rivers were directly related to the visible attributes used in human judgments. We suggest that, regardless of variability among individual stakeholders, observable characteristics may be the foundation for a common understanding of water quality in rivers.
**Introduction**

The ability to integrate cultural values into water resource management is becoming increasingly important as climate and landscape change become more salient and polarized in public opinion. Stakeholder engagement in water resources management is as important as application of scientific knowledge \([\text{Wheater and Gober, 2015}]\), and presenting water quality assessments in terms of impacts to human activities and values will make them more meaningful to the public \([\text{Keeler et al., 2012}]\). For example, the US Environmental Protection Agency (US EPA) have encouraged states to develop numeric nutrient criteria, and have advocated science to achieve this goal \(\text{(e.g., US EPA 2010)}\). While it is acknowledged that changes in water characteristics caused by excessive nutrients can compromise recreational use \(\text{(US EPA, 2000)}\), the US EPA has not yet included methods that evaluate human values or perceptions in criteria development strategies. Human perceptions of water quality (WQ) should be evaluated so that citizen values are justly considered in the protection of water bodies.

Optical water quality (OWQ) refers to the suitability of a water body, as defined by its optical properties, to support biodiversity and/or human welfare \([\text{Kirk, 1988}]\). Physical, chemical, and biological assessments can quantify WQ in the biosphere in terms of concentrations of sediments, nutrients, and pollutants, and their effects on aquatic systems. But, water quality in regard to the human environment is a more complicated subject—cultural, spiritual, and aesthetic values are much more difficult to quantify. Recent studies in both the hydrologic and the social sciences have broadened the concept of ecosystem services to help quantify the social value of water quality in the environment \(\text{(e.g., Keeler et al. 2015, Nelson et al. 2015, Castro et al. 2016)}\). Still, research projects integrating the two sciences are somewhat rare \(\text{(Egan et al., 2009; Brauman, 2015)}\). Despite myriad suggestions to use holistic approaches to environmental
management [Falkenmark, 1977; NRC, 2004; Lall, 2014], ecology and the human environment are still often considered separately because of the difficulty of relating quantitative data to human values.

Early work connecting quantitative values of OWQ with human perceptions related mean Secchi depth and total phosphorus in lakes in Minnesota and Vermont to recreational impairment [Heiskary and Walker, 1988; Smeltzer and Heiskary, 1990]. Researchers in New Zealand linked measured water clarity and color to judged recreational suitability in rivers [Smith et al., 1991, 1995; Smith and Davies-Colley, 1992]. More recently, Egan et al. (2009) determined reduced water clarity and increased total phosphorus concentrations to be directly related to a decrease in recreational trips to Iowa lakes. Suplee et al. (2009) quantitatively linked benthic algae biomass in Montana streams to recreational desirability. Keeler et al. (2015) found that Minnesota and Iowa lakes that had greater average water clarity received more frequent recreational visitation. Smith et al. (2015) examined WQ measurements alongside visual assessments of recreational ability in streams of New York State and proposed thresholds for total phosphorus, total nitrogen, suspended chlorophyll $a$, and turbidity that would maintain desirability. Our study sought to expand on these by examining the cognitive structures that inform human judgments of aquatic environments. Pile sorting is a structured interviewing method that offers respondents a set of cards, images, or items which they are instructed to organize into groups that go together, without providing suggestions or examples [Weller, 2015]. The pile sort exercise was designed to elicit and explore the dimensions guiding variability in cultural domain perceptions [Trotter et al., 2015], rather than individual preferences, decisions, or behaviors.

Culture is the set of learned behavior patterns and shared values and beliefs of a social group [Goodenough, 1981], and environmental perceptions can be a product of a shared cultural
framework [Cottet et al., 2013]. Perceptions of WQ are also influenced by the individual senses of the observer with respect to all of the complexities of his or her own prior experiences and associations [Coughlin, 1976]. The study of ethnohydrology has developed, from its inception by William Back (1981), to describe the culturally constituted knowledge of water [Gartin et al., 2010]. Ethnohydrology studies have examined an array of issues, ranging from urban residents’ views of water management [Gartin et al., 2010], to the imaginings of long-term changes of water in the environment by school-aged children [Vins et al., 2014]; from the cultural understanding of connections between water quality and disease [Brewis et al., 2013], to perceived injustices of institutions responsible for water distribution [Wutich et al., 2013]. A mental model is a functional cognitive structure that allows individuals to understand and make decisions regarding their environment [Jones et al., 2011; Lynam and Brown, 2012]. External information is processed through an evolving individual mental model, elicitation of which may strengthen conservation planning and implementation [Biggs et al., 2011]. Ethnohydrology studies can help examine cultural paradigms and may allow for the development of a common mental model of human dimensions of water that will enhance communication among stakeholders, scientists, and policy makers [West et al. 2016]. To represent the full significance of water in our environment we must recognize perceptual, emotional, spiritual, and aesthetic ideals [Burmil et al., 1999]. The complete understanding of water environments required to inform sustainability science can only be achieved by integration of the hydrologic and social sciences [Braden et al., 2009; Orlove and Caton, 2010; Linton, 2014]. As such, river monitoring and management can be strengthened by incorporating both ecological and human values [Harmsworth et al., 2011].
This study aimed to contribute to an integrative understanding of human perceptions and OWQ in rivers by investigating two hypotheses: (1) wide agreement exists among stakeholders in judgments of similarity when observing aquatic conditions; and (2) judgments of similarity will be related to measurable water quality attributes because the effects of chemical and physical variability are often directly visible. The overarching objective of this paper is to demonstrate the associations between scientific environmental indicators and human perceptions of rivers, using rivers of the southwestern Ozarks as a case study.

Materials and Methods

Study area: Southwestern Ozarks, USA

Five rivers in the southwestern Ozarks of Arkansas, US were chosen for their regional popularity as recreational destinations. Four of the five rivers in this study are held under special designations by the States of Arkansas and Oklahoma: the Buffalo, Kings, and Mulberry Rivers are designated extraordinary resource waters by the State of Arkansas; the Buffalo and Mulberry Rivers are also natural and scenic waterways by the State of Arkansas; the Illinois River is designated ecologically sensitive by the State of Arkansas and also as a scenic river by the State of Oklahoma. The Illinois river has reaches listed as impaired for aesthetics by phosphorus, and for primary contact recreation by pathogen indicators [OK DEQ, 2014]. The fifth river, War Eagle Creek is simply designated as a primary contact recreation waterway. The five rivers in this study are characteristic of the region’s riffle-pool morphology, with bedrock, rubble, and gravel dominating the streambeds [Adamski et al., 1995].

The chosen rivers represent a range of land use characteristics (Table 1), flow patterns, and chemistry. All five rivers originate in the sandstone, shale, and siltstone of Boston Mountain

113
(BM) ecoregion. Four of the rivers then cut deeply through the limestone and dolomite of the Ozark Highlands (OH) ecoregion, providing a narrow, but critical range of WQ variability for the region. Streams of the BM ecoregion generally have exceptional water quality, with low nutrient and mineral concentrations; whereas karst geology and increasing human alteration contribute to higher alkalinity, dissolved solids, and nutrient concentrations in the OH ecoregion [Adamski et al., 1995; Woods et al., 2004]. The sampling location on each river was chosen to coincide with the following US Geological Survey gaging stations to allow us to continuously monitor flow conditions via WaterWatch (waterwatch.usgs.gov): Buffalo River near St. Joe, AR; Illinois River south of Siloam Springs, AR; Kings River near Berryville, AR; Mulberry River near Mulberry, AR; War Eagle Creek near Hindsville, AR.

Data Collection

Site visits were initiated by precipitation events that induced flows favorable for kayak and canoe recreation during Spring and early Summer of 2014 (April through June). Data were collected at intervals ranging from several times per day to approximately once every 2-5 days as flow receded, based on observation of the river’s response to precipitation. Black disk visibility (BDV) was recorded as the average of three visual distance measurements with a horizontal black disk device [Davies-Colley 1988]. This method is similar to the Secchi disk, but uses an inverted periscope and an all-black target to measure visual clarity underwater. Because the measurement is made horizontally underwater, BDV is useful in shallow rivers and is directly related to the inherent optical properties of the water [Davies-Colley, 1988; Steel and Neuhauser, 2002; Zaneveld and Pegau, 2003]. At each visit we photographed underwater conditions at wrist depth to capture both the water background and the substrate. We collected three liters of water at each sampling occasion in acid-washed bottles and immediately stored them on ice and
transported them to the lab at the University of Arkansas in Fayetteville, AR. Water samples were kept at ~4°C and processed within 48 hours. We used a Turner Designs Model 7200 Trilogy™ fluorometer fitted with a turbidity module, and calibrated with a blank sample of deionized water and AMCO Clear® turbidity standards of 10 and 100 NTU. We recorded the average turbidity of three rapidly consecutive measurements on each sample. Total suspended solids (TSS) were measured according to standard methods [APHA, 2005] using Whatman GF/F 47mm glass fiber filters. We also filtered water samples through Whatman GF/F 25mm glass fiber filters for analysis of suspended chlorophyll a (chl-a) and particulate phosphorus (PP) concentrations. Filters were kept frozen until analysis. We used the Trilogy™ fluorometer to measure chl-a, via the acid digestion method, following overnight extraction with acetone. We also used the Trilogy™ fluorometer, fitted with an absorbance module, to measure PP using the 1% persulfate digestion and ascorbic acid colorimetric method [APHA, 2005]. Prior to statistical analysis, we log$_{10}$ transformed concentration values because water quality data typically exhibit lognormal distribution [Hirsch et al., 1991].

We chose 26 photographs independently of WQ measurements, including one photograph that was “staged”, i.e., the substrate was stirred up intentionally (WQ parameters for this photograph were not included in statistical analyses). The final set of photographs was settled upon so as to be fully representative of the visual range of OWQ conditions throughout the sampling period without being too overwhelming for respondents. After the photographs were chosen, we noted two occasions where we selected two photographs from the same sampling event (Figure 1). Because our inspection judged the images to have noticeable visible differences, we elected to keep the duplicates to allow us to consider what effect the photography might introduce. We matched tiles of the Munsell® Color charts for plant tissue [Munsell Color,
1977] to each photograph to give numeric values to the dominant Munsell hue (color), Munsell value (lightness), and Munsell chroma (saturation) of the image. We assigned a brief written survey and pile-sort task with the 26 photographs to 167 respondents (151 completed pileSorts) at four different locations: 38 respondents at the Arkansas Water Resources Center annual conference 2014 (AWRC), 59 at the Arkansas Chapter of the American Fisheries Society annual meeting 2015 (AAFS), 39 at the 2015 Jungle Boater Race at Mulberry River (RACE), and 31 respondents in front of a local grocery/department store (SHOP). Each respondent was asked to sort the images “by whatever criteria you deem meaningful”. This wording was specified in such a way as not to suggest respondents sort by preference or any other proposed criteria.

The written survey was administered prior to the pile-sort task to ensure that each respondent was equally aware of the topic when they approached the pile-sort, and included the following questions:

- Education Level: High School, Some College, Associate Degree/Professional Certification, Bachelor’s Degree, Advanced Degree

- How knowledgeable are you about water quality in rivers? 1 (Very little knowledge) – 7 (Expert)

- How experienced are you with recreation on rivers (kayaking, canoeing, fishing, etc.)? 1 (Very little experience) – 7 (Expert)

- How important to you is water quality in rivers? 1 (Not important) – 7 (Very important)

- How important to you is water clarity in rivers? 1 (Not important) – 7 (Very important)

For comparisons presented in this report, we separated respondents into two subgroups for each of the first three questions.
Statistical Analyses

A non-metric multidimensional scaling (NMDS) procedure was carried out in Anthropac [Borgatti, 1996] to generate a two-dimensional proximity (dissimilarity) matrix of the photographs from the entire set of respondents’ pile sorts [Weller and Romney, 1988]. We repeated the procedure for 14 subgroups of respondents as defined by survey responses. Upon confirmation of an acceptable stress value in 2 dimensions (less than 0.313 for 26 items; Sturrock and Rocha 2000), we used the NMDS coordinates in further analyses. The NMDS coordinates of 25 photographs (staged photograph removed) and the corresponding WQ measurements for each photograph were used to perform a property fitting analysis (PROFIT) in UCINET 6 [Borgatti et al., 2002]. PROFIT is a multiple linear regression technique wherein a vector representing a dependent variable, in this case a WQ parameter, is fitted to the independent X and Y coordinates of the photographs in the NMDS [Kruskal and Wish, 1978]. The regressed vector runs through the origin and is an indicator of the direction of increasing value of the WQ parameter with respect to the locations of photographs on the NMDS. PROFIT analysis allowed us to test the hypothesis that a given WQ variable was an underlying dimension in pile sorting.

We derived distance matrices from the NMDS coordinates and performed agglomerative hierarchical cluster analyses with the complete set of pile sorts and those of the subgroups using the average-link in R [R Core Team, 2015] to identify which photographs tended to exist together within the NMDS. Because of the multitude of indices for determining the optimal number of clusters, we selected two methods that use different calculation procedures, the Duda and Hart index [Duda and Hart, 1973] and the gap index [Tibshirani et al., 2001]. The Duda and Hart index is an iterative local optimization method that uses the sum of squared errors within clusters, sample size, and the number of dimensions to calculate a critical value which is
compared to a standard score, and has been shown to perform reliably with relatively small sample sizes [Milligan and Cooper, 1985]. The gap index is a global optimization procedure that determines the most likely number of clusters by comparing the dispersion against the null distribution [Tibshirani et al., 2001]. We calculated both indices using the NbClust package for R [Charrad et al., 2014]. We further investigated each WQ variable among the clusters with one-way analysis of variance (ANOVA) for each WQ variable. If ANOVA results were significant at the 95% confidence level, we followed with pairwise t-tests among the clusters using the Bonferroni p-value correction. We also visually assessed NMDS plots of respondents by demographics and survey responses.

Results

Respondent demographics

We recruited 167 total respondents, for which 151 completed pile-sorts were used. Sixteen were thrown out due to documentation error. General demographics of the 151 respondents are shown in Table 2. Regardless of our solicitation of responses outside of the university in an attempt to represent a greater range of education levels, it seemed that individuals with a Bachelor’s degree or higher were both more common at our solicitation events and more willing to participate in the survey. Fifty percent of respondents at the two non-academic events (BOAT and SHOP) held a Bachelor’s degree or higher. Thus, the range of education levels was probably not representative of the general population.

Multidimensional scaling and property fitting analysis

The NMDS plot with an acceptable stress value of 0.121 (Figure 2) illustrates the overall
solution to the pile-sort. Photographs frequently placed into the same pile are closer together, and those rarely piled together are farther apart in the NMDS plot. Property fitting analysis allowed us to investigate the relationship between our measured WQ variables and the coordinates of the NMDS plot. PROFIT resulted in significant relationships among NMDS coordinates and WQ variables ($p \leq 0.001$) for BDV, turbidity, TSS, and PP, with multiple R values of 0.749, 0.707, 0.667, and 0.673, respectively. The PROFIT vectors show the general direction of increasing value for each WQ variable (Figure 3). Turbidity and TSS generally increased from top-right to bottom-left, and inversely for BDV. The PROFIT regression vector for PP correlated closely with the vertical axis (Figure 3d). Suspended chl-$a$ was not significantly related to the NMDS coordinates in PROFIT analysis.

*Hierarchical cluster analysis*

Hierarchical cluster analysis allowed us to identify groupings within the NMDS solution. The Duda and Hart index suggested a 6-cluster solution (Figure 2, indicated by shaded ellipses); the gap index indicated 3 clusters were optimal (Figure 2, indicated by dark numerals). Investigation of WQ measurements among each group by ANOVA returned significant differences ($p<0.05$) for TSS, turbidity, BDV, and PP for both the 3- and the 6-cluster solutions. Munsell hue, value, and chroma, and concentrations of suspended chl-$a$ were not significantly different among the groups. In the 6-cluster solution, multiple comparisons showed Groups 1 and 6 were significantly different ($p<0.05$) from one another for every measured water quality variable except chl-$a$ (Figure 4, left column). Groups 2 and 3 were intermediate for BDV and turbidity. Groups 2 through 5 were intermediate for TSS. Groups 2 through 4 were intermediate for PP. For the 3-cluster solutions, multiple comparisons confirmed Groups 1 and 3 were significantly different ($p<0.05$) from one another for every measured water quality variable.
except suspended chl-\(a\) (Figure 4, right column). Group 2 was an intermediate between Groups 1 and 3 for TSS. Group 1 was significantly different from both Groups 2 and 3 for BDV, turbidity, and PP.

Upon separating the pile sorts by survey responses and solicitation venue, and generating NMDS plots of photographs, subgroup cluster analysis results were similar to that of the entire data set. We were unable to identify patterns in NMDS plots of respondents by subgroups. All NMDS plots were within acceptable stress limits for representation in two dimensions. Differences among groups existed in the optimal number of clusters determined by the Gap and Duda and Hart indices (Table 3). However, within the number of optimal clusters indicated by the Duda and Hart index for the 14 subgroups (Table 2, left column), the six photographs of Group 1 of the 6-cluster solution (Figure 2, bottom) remained together in all but one subgroup. A photograph dominated by a cloudy bright orange with no obvious suspended particulates was isolated into its own cluster in the 6-cluster solution for AAFS respondents. Similarly, the five photographs of Group 5 (Figure 2, top left) remained within a single cluster in all but one subgroup. In the 7-cluster solution of female respondents, the leftmost photograph of Group 5 was placed in a separate group with the leftmost photograph of Group 3 (Figure 2, shaded ellipses). For the sake of greater simplicity, and because the 3- and 6-cluster solutions are analogous, our forthcoming discussion will focus on the 3-cluster solution.

**Discussion**

The ability to link quantitative OWQ variables to human perceptions is predicated by our two hypotheses. Our results supported both hypotheses: (1) although perceptions varied among individuals, there were no apparent dissimilarities according to age, gender, experience, or
education of respondents, and (2) judgments of underwater conditions in rivers were related to measurable OWQ variables that influence visible characteristics. This study furthers the understanding of human perceptions of water quality beyond simple preference because respondents were not encouraged to consider any specific characteristics outside those triggered in their own cognitive processing of the images. These associations between human perceptions and scientific environmental indicators may lend insight into water resources management and communication.

Based on previous investigations of human perceptions of WQ [Smeltzer and Heiskary, 1990; Smith and Davies-Colley, 1992; Smith et al., 1995], we were not surprised to note that respondents reacted to clarity and color, both of which were commonly mentioned when asked what criteria were used to group the photographs. Visual clarity trended from low visibility at the bottom of the NMDS plot to greater visibility in the photographs toward the top and right (Figure 2). Indeed, the strongest correlation in the PROFIT analysis (multiple R = 0.749) was that of BDV (Figure 3a). Notably, photographs with yellow hues were not relegated to the lower edge of the NMDS. A few with greater visibility and brighter color were scattered throughout (Figure 2). Thus, clarity might play a dominant role in perceptions, one that can sometimes override color.

While we did not conclude statistical differences in Munsell hue, value, or chroma among the groups, we can see in the NMDS plot that muted browns and grays were generally situated toward the bottom-left, and brighter blues and greens toward the top-right (Figure 2). The lack of statistical difference may have been because there was a relatively narrow range by the Munsell scale, or could be an effect of using the Munsell system in classification of non-opaque materials, for which it was not designed [American Society for Testing and Measurement, 1968].

We propose that measured physicochemical parameters are tightly linked to the visual
criteria that influence human perceptions. Considering the images as grouped by the 3-cluster solution of hierarchical cluster analysis (Figure 2), brighter colors and greater visibility were common to Groups 2 and 3. Whereas, darker, brown waters with low visibility were isolated to Group 1. Means of BDV, turbidity, TSS, and PP were all significantly different between Groups 1 and 3 (Figure 4, right column). This was substantiated by PROFIT analysis (Figure 3), which significantly related these WQ variables to the NMDS coordinates of the complete pile-sort data. Suspended chl-a concentrations were the exception, likely because they were relatively low throughout (geometric mean = 1.45 µg/L, maximum concentration = 4.11 µg/L). PROFIT analysis implied quantitative measures of BDV, turbidity, TSS, and PP were, either consciously or unconsciously, involved in respondents’ arrangement of the photographs. However, because there was separation in the NMDS plot by variables that cannot be explained solely with these physical measurements, the vectors drawn by PROFIT should not be used as predictors of human perceptions.

Because mean values of Groups 2 and 3 were not significantly different from one another for any of our measured WQ variables, we were prompted to return to the photographs for an explanation. While clarity and color may be strongly influential for recreation [Smith and Davies-Colley, 1992], features of the substrate are noticed as well. The presence of sediment of different types and sizes can influence human perceptions of rivers [Cottet et al., 2013; Le Lay et al., 2013]. We propose that judgments are also influenced by periphyton, that is, the assemblage of algae, bacteria, and microbes attached to the substrate. Though we did not quantitatively assess for periphyton, it was commonly mentioned by respondents (as “algae”). Group 2 included only photographs that had relatively bare rocks. Whereas, the rocks in Group 3 appeared more algae covered. This agreed with results from Smith et al. [2015], who concluded
periphyton growth, along with clarity, as significant predictors of recreational impairment as judged by field crews. Suplee et al. [2009] also valuably linked periphyton abundance to desirability for recreation. While both of these studies asked respondents outright about algae cover, our study suggests that the consideration is perceptual, and exists without direct solicitation of the subject.

Many researchers falsely believe communication barriers among scientists, policy makers, and the public to be a result of “public ignorance” [Nisbet and Scheufele, 2009]. There are numerous initiatives with goals of educating the public in an effort to encourage greater regard for water quality. This “deficit model” of communication is ineffective and fails to consider the many other factors that play larger roles in guiding human perceptions [Groffman et al., 2010]. We might be able to investigate, then, where breakdowns in communication and evaluation among stakeholders truly occur. Other studies using similar elicitation methods on a wide range of subjects have found notable differences between “experts” and “novices” (e.g., Solomon 1997; Nolan 2002; Shipman and Boster 2008), and even specific type of expertise in a given subject [Medin et al., 1997]. Garro [1986] and Boster [1985] found higher agreement among experts, which may imply that expertise results in the convergence of ideas and priorities. But, Boster and Johnson [1989] and Nolan [2002] discovered less agreement among experts, suggesting a greater diversity of knowledge might explain individual divergence. NMDS plots of respondents in our study did not expose any trends among self-described knowledge, experience, or education level, supporting the idea that judgments of WQ in rivers are based on culturally-constructed views that exist more broadly within the population of stakeholders. Further, cluster analyses of 14 sets of NMDS coordinates of photographs by subgroups generally corresponded well with our cluster solutions of the entire set of 151 respondents. Aside from two subtle
exceptions described previously, our observations suggested particularly strong agreement in perceptions of aquatic environments among respondents in the upper and lower ranges of measured WQ variables represented in our 26 photographs, regardless of the type of stakeholder.

While standards using the horizontal black disk visibility method have not been established in the US, the New Zealand Ministry for the Environment has published guidelines stating that BDV should exceed 1.6 m (Figure 4a & b, dashed line) in waters managed for contact recreation [Ministry for the Environment 1994]. Davies-Colley et al. [1995] found that 75% of recreational users rated BDV values of 1.2 meters or greater as “suitable” or better for bathing (Figure 4a & b, dotted line). The upper quartile of BDV in Group 1 in the 3-cluster solution, which may represent conditions judged as less desirable, was just below that (1.12 m). Though we did not seek preference, per se, our study of WQ judgments is comparable to recreational users’ rating of suitability for bathing found by Davies-Colley et al. [1995]. The Arkansas Pollution Control and Ecology Commission [2011] have developed turbidity standards of 17 and 19 NTU for all flows in rivers in the Ozark Highlands and Boston Mountains ecoregions, respectively (Figure 4c & d, dotted and dashed lines). Considering these standards alongside the 3-cluster solution of our study, the upper quartiles of turbidity measurements for photographs in Groups 2 and 3 were well below both thresholds. The median of Group 1 (14.6 NTU) was also below these standards. This suggests human perceptions of OWQ may not wholly agree with existing limits set to maintain ecological integrity. While Smith et al. [2015] proposed a turbidity value of 4.0 NTU as a threshold for avoiding substantial impacts to recreation in wadeable New York streams, our analysis may allow for a less conservative value for larger recreational rivers of the Ozarks. Because Group 2 of the 3-cluster solution included the images that most respondents agreed upon as belonging together, and generally represented a
mid-range in WQ that was still distinctly separate from the tight grouping of Group 1, we may be able to extend our cluster analysis and multiple comparison results to suggest turbidity, TSS, and/or PP thresholds for human judgments by using the upper quartiles of Group 2 (Figure 4, dash-dotted lines). This would infer a turbidity limit of 8.6 NTU, a TSS limit of 8.5 mg/L, and a PP limit of 10.2 µg/L.

We acknowledge that photography may not necessarily be the best representation of the true observable conditions underwater. Our best attempts were made to minimize variation; however, automatic camera operations may somewhat misrepresent the relative conditions by correcting the exposure for instantaneous underwater lighting. We did consider this when choosing photographs and have two sampling occasions that were represented twice in the pile-sort images (Figure 1). In the first set of duplicates (Figure 1a & b) the primary difference is the camera angle, which affected the dominant color of the image and the ability to discern details of the substrate. The two were placed in different groups by cluster analysis of the NMDS coordinates, Groups 2 and 3, respectively. The other set of duplicates (Figure 1c & d) have more subtle differences. While they are nearly identical in color, one image shows rays of light and the surface of the water (Figure 1c). They were both placed into Group 3 by cluster analysis. Even with the potential weaknesses, photographs may be the most practical method for assessing responses of groups while controlling for a multitude of outside influences that may affect perceptions, such as odor, flow, litter, and landscape [West et al. 2015].

Conclusions

We sought to examine human perceptions of WQ in rivers using photographs of the aquatic environment to elicit and examine mental models of stakeholders. Our results imply that
individuals may deploy similar cognitive processes to discern differences among images of aquatic conditions in rivers, and these judgments can be linked to commonly measured OWQ variables. We suggest some important physical and chemical parameters of WQ may be communicated meaningfully across groups in terms of how they relate to visible attributes. This ethnohydrology study moves toward linking a range of quantitative WQ parameters to culturally-constructed user perceptions that can inform resource management. The consensus among individuals here may mean we have come one step closer to understanding the differences—or lack thereof—in perceptions among groups of stakeholders in water resources.
References


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Borgatti, S., M. Everett, and L. Freeman (2002), Ucinet for Windows: Software for social network analysis,


R Core Team (2015), R: A language and environment for statistical computing.,


**Tables**

**Table 1. Summary of respondent demographics**

<table>
<thead>
<tr>
<th>Demographic</th>
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<td>High school</td>
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<td>Some college</td>
<td>26</td>
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<tr>
<td>Associate degree/professional certification</td>
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Note: nonresponses existed where n does not add to 151
Table 2. Subgroup cluster analysis results

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</table>

Note: nonresponses existed where n does not add to 151

† Yes/No; indicates whether all photographs in the named group of the overall 6-cluster solution were also included in a single cluster within the subgroup
Figures

**Figure 1.** Sets of photographs representing duplicates of field measurements, a. and b. are duplicate measures; c. and d. are duplicate measures
Figure 2. Nonmetric multidimensional scaling plot with separations by hierarchical cluster analysis. Ellipses with light numerals capture each group of the 6-cluster solution; dark numerals indicate the 3-cluster solution.
Figure 3. Property fitting analysis vectors overlying nonmetric multidimensional scaling plot, a. black disk visibility; b. turbidity; c. total suspended solids; d. particulate phosphorus
Figure 4. Boxplots of water quality measurements for photographs grouped by hierarchical cluster analysis, colors indicate results of multiple comparisons, boxes including the same colors were not significantly different; dashed lines and dotted lines indicate existing regulatory limits; dash-dotted lines indicate potential limits proposed in this study.
VI. Epilogue

The rivers of the Ozarks are revered for their ecologic and scenic value, contributing both economically and culturally to the Ozark region. In addition to protecting aquatic ecosystems and human health, the Clean Water Act explicitly protects aesthetics and recreation in surface waters of the United States [US Congress, 1972], but most regulatory agencies have yet to propose methods considering the human dimension in developing quantitative water quality standards. There is considerable non-governmental involvement in water resources conversations in the Ozark region (e.g. Illinois River Watershed Partnership, Beaver Watershed Alliance, Arkansas Watershed Advisory Group, Kings River Watershed Partnership, Ozark Society, and the Nature Conservancy), and formation of these groups is encouraged by the Arkansas Department of Environmental Quality [ADEQ, 2014]. Effective communication among stakeholders in water resources can best be achieved with an interdisciplinary perspective, considering the physical and social factors influencing human values.

My research was aimed at the intersection between optical water quality and human perceptions of water quality. I focused on receding flow in five popular recreational rivers of the Ozarks during the spring and summer of 2014 and 2015 in order to investigate optical water quality dynamics during periods likely to be experienced by recreational users. Understanding the characteristics of recreational rivers in the Ozarks is integral to maintaining ecosystem health, perceived value and appeal, regional economic significance, and in shaping management strategies. My aim was three-fold: (1) to characterize variability in optical water quality and particulate concentrations in five Ozark rivers in relation to flow events, (2) to evaluate optical water quality methods for application in resource management, and (3) to determine how human perceptions of water quality relate to measured water quality in rivers. Chapter one described the
controls on optical water quality in inland waters, how it is measured, and how it might influence human perceptions. Chapter two investigated relationships among optical water quality measurements and suspended sediment concentrations. Chapter three characterized particulate dynamics as flow recedes in five Ozark rivers, and discussed how optical water quality might contribute to a better understanding during times of rapid variability in rivers. Finally, Chapter IV linked common influences in human judgments of water quality to measured water quality variables, and suggested a potential limits of scientific parameters related to human perceptions—giving us a place to start in defining aesthetic and recreational desirability. My research sought to close a gap in scientific knowledge concerning how citizens perceive water quality in rivers of the Ozarks to support a more effective discourse among stakeholder groups.
References


Appendix: Institutional Review Board Documentation
MEMORANDUM

TO: Amie West
    Thad Scott
    Justin Nolan

FROM: Ro Windwalker
      IRB Coordinator

RE: PROJECT CONTINUATION

IRB Protocol #: 14-07-007

Protocol Title: Perceptions and Relationships with Optical Water Quality in Ozark Rivers

Review Type: ☑ EXEMPT ☐ EXPEDITED ☐ FULL IRB

Previous Approval Period:
    Start Date: 07/14/2014
    Expiration Date: 07/13/2015

New Expiration Date: 07/13/2016

Your request to extend the referenced protocol has been approved by the IRB. If at the end of this period you wish to continue the project, you must submit a request using the form Continuing Review for IRB Approved Projects, prior to the expiration date. Failure to obtain approval for a continuation on or prior to this new expiration date will result in termination of the protocol and you will be required to submit a new protocol to the IRB before continuing the project. Data collected past the protocol expiration date may need to be eliminated from the dataset should you wish to publish. Only data collected under a currently approved protocol can be certified by the IRB for any purpose.

This protocol has been approved for 230 total participants. If you wish to make any modifications in the approved protocol, including enrolling more than this number, you must seek approval prior to implementing those changes. All modifications should be requested in writing (email is acceptable) and must provide sufficient detail to assess the impact of the change.

If you have questions or need any assistance from the IRB, please contact me at 109 MLKG Building, 5-2208, or irb@uark.edu.
IRB Project Number

UNIVERSITY OF ARKANSAS INSTITUTIONAL REVIEW BOARD
PROTOCOL FORM

The University Institutional Review Board recommends policies and monitors their implementation, on the use of human beings as subjects for physical, mental, and social experimentation, in and out of class. . . Protocols for the use of human subjects in research and in class experiments, whether funded internally or externally, must be approved by the (IRB) or in accordance with IRB policies and procedures prior to the implementation of the human subject protocol. . . Violation of procedures and approved protocols can result in the loss of funding from the sponsoring agency or the University of Arkansas and may be interpreted as scientific misconduct. (see Faculty Handbook)

Supply the information requested in items 1-14 as appropriate. Type entries in the spaces provided using additional pages as needed. In accordance with college/departmental policy, submit the original and one copy of this completed protocol form and all attached materials to the appropriate Human Subjects Committee. In the absence of an IRB-authorized Human Subjects Committee, submit the original of this completed protocol form and all attached materials to the IRB, Attn: Compliance Officer, ADMN 210, 575-2208. Completed form and additional materials may be emailed to irb@uark.edu. The fully signed signature page may be scanned and submitted with the protocol, by FAX (575-3846) or via campus mail.

1. Title of Project Perceptions and Relationships with Optical Water Quality in Ozark Rivers

2. (Students must have a faculty member supervise the research. The faculty member must sign this form and all researchers and the faculty advisor should provide a campus phone number.)

<table>
<thead>
<tr>
<th>Name</th>
<th>Department</th>
<th>Email Address</th>
<th>Campus</th>
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<tbody>
<tr>
<td>Amie West</td>
<td>Environmental Dynamics</td>
<td></td>
<td>Fayetteville</td>
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<tr>
<td>Co-Researcher</td>
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<td>Co-Researcher</td>
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<td>Thad Scott</td>
<td>Crop, Soil &amp; Env. Science</td>
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<td>Fayetteville</td>
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<td>Justin Nolan</td>
<td>Anthropology</td>
<td></td>
<td>Fayetteville</td>
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</tbody>
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3. Researcher(s) status. Check all that apply.

[ ] Faculty [ ] Staff [X] Graduate Student(s) [ ] Undergraduate Student(s)

4. Project type

[ ] Faculty Research [X] Thesis / Dissertation [ ] Class Project [ ] Independent Study /

5. Is the project receiving extramural funding? (Extramural funding is funding from an external research sponsor.)

[X] No [ ] Yes. Specify the source of funds
IRB Project Number

6. Brief description of the purpose of proposed research and all procedures involving people. Be specific. Use additional pages if needed. (Do not send thesis or dissertation proposals. Proposals for extramural funding must be submitted in full.)

Purpose of research:

The proposed research aims to describe how users of rivers in Northwest Arkansas perceive water quality and to gain information about how optical water quality is interpreted and valued. It will also investigate how these perceptions relate to established scientific parameters of water quality.

Procedures involving people:

A survey has been developed to employ several accepted methods of qualitative research (attached).

- Likert-style questions are designed to define basic demographics and help classify respondents' experience with, and understanding of, river dynamics.
- True/False questions are designed to allow researchers to perform a cultural consensus analysis and identify any shared understandings of the river.
- Open-ended narrative questions are designed to allow a correspondence analysis to identify themes within possible subsets of respondents.
- A series of 20 images of rivers in a spectrum of clarity/flow states will be presented. A pile sorting analysis will be performed to identify common themes.
  - Respondents will be asked to organize photos by any criteria they deem meaningful. They will then be asked to verbally describe how they chose to organize the photos. The investigator will note verbal responses, and the organization pattern will be photographed (respondent will not be photographed).

7. Estimated number of participants (complete all that apply)

   _____ Children under 14   _____ Children 14-17   _____ UA students  (18yrs and older)    50   Adult non-students

8. Anticipated dates for contact with participants:

    First Contact    July 15, 2014    Last Contact    July 16, 2014

9. Informed Consent procedures: The following information must be included in any procedure: identification of researcher, institutional affiliation and contact information; identification of Compliance Officer and contact information; purpose of the research, expected duration of the subject's participation; description of procedures; risks and/or benefits; how confidentiality will be ensured; that participation is voluntary and that refusal to participate will involve no penalty or loss of benefits to which the subject is otherwise entitled. See Policies and Procedures Governing Research with Human Subjects, section 5.0 Requirements for Consent.

   [ ] Signed informed consent will be obtained. Attach copy of form.
   [ ] Modified informed consent will be obtained. Attach copy of form.
   [X] Other method (e.g., implied consent). Please explain on attached sheet.
   [ ] Not applicable to this project. Please explain on attached sheet.

10. Confidentiality of Data: All data collected that can be associated with a subject/respondent must remain confidential. Describe the methods to be used to ensure the confidentiality of data obtained.

    Personally identifying information will not be collected.
11. Risks and/or Benefits:
   Risks:  Will participants in the research be exposed to more than minimal risk?  Yes  X  No
   Minimal risk is defined as risks of harm not greater, considering probability and magnitude, than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests. Describe any such risks or discomforts associated with the study and precautions that will be taken to minimize them.

   Benefits:  Other than the contribution of new knowledge, describe the benefits of this research.

   Results obtained from the project will allow future investigators to better understand the associations between quantitative environmental indicators and human perceptions of the resource. It is our hope that this understanding can contribute to better communication between scientific investigators, recreational users, environmental management agencies, and other interested groups.

12. Check all of the following that apply to the proposed research. Supply the requested information below or on attached sheets:

   A. Deception of or withholding information from participants. Justify the use of deception or the withholding of information. Describe the debriefing procedure: how and when will the subject be informed of the deception and/or the information withheld?

   B. Medical clearance necessary prior to participation. Describe the procedures and note the safety precautions to be taken.

   C. Samples (blood, tissue, etc.) from participants. Describe the procedures and note the safety precautions to be taken.

   D. Administration of substances (foods, drugs, etc.) to participants. Describe the procedures and note the safety precautions to be taken.

   E. Physical exercise or conditioning for subjects. Describe the procedures and note the safety precautions to be taken.

   F. Research involving children. How will informed consent from parents or legally authorized representatives as well as from subjects be obtained?

   G. Research involving pregnant women or fetuses. How will informed consent be obtained from both parents of the fetus?

   H. Research involving participants in institutions (cognitive impairments, prisoners, etc.). Specify agencies or institutions involved. Attach letters of approval. Letters must be on letterhead with original signature; electronic transmission is acceptable.

   I. Research approved by an IRB at another institution. Specify agencies or institutions involved. Attach letters of approval. Letters must be on letterhead with original signature; electronic transmission is acceptable.

   J. Research that must be approved by another institution or agency. Specify agencies or institutions involved. Attach letters of approval. Letters must be on letterhead with original signature; electronic transmission is acceptable.

13. Checklist for Attachments

   The following are attached:

   ☐ Consent form (if applicable) or

   X  Letter to participants, written instructions, and/or script of oral protocols indicating clearly the information in item #9.

   ☐ Letter(s) of approval from cooperating institution(s) and/or other IRB approvals (if applicable)

   X  Data collection instruments
14. Signatures

I/we agree to provide the proper surveillance of this project to insure that the rights and welfare of the human subjects/respondents are protected. I/we will report any adverse reactions to the committee. Additions to or changes in research procedures after the project has been approved will be submitted to the committee for review. I/we agree to request renewal of approval for any project when subject/respondent contact continues more than one year.

Principal Researcher

Co-Researcher

Co-Researcher

Co-Researcher

Faculty Advisor
PROTOCOL APPROVAL FORM
(To be returned to IRB Program Manager with copy of completed protocol form and attachments)

Human Subjects Committee Use Only  (In absence of IRB-authorized Human Subjects Committee, send protocol to IRB.)

Recommended Review Status

9 Human Subjects Committee can approve as exempt because this research fits in the following category of research as described in section 9.02 of the IRB policies and procedures (Cite reasons for exempt status):

Printed Name and
Signature of the HSC Chair __________________________ Date

****************************************************************************************************
** 9 Expedited Review by a designated member of the IRB because this research fits in the following category of research as described in section 9.03 of the IRB policies and procedures (Cite reasons for expedited status):

Printed Name and
Signature of the HSC Chair __________________________ Date

****************************************************************************************************
*** 9 Requires Full Review by the IRB because this research fits in the following category of research as described in section 9.04 of the IRB policies and procedures (Cite reasons for full status):

Printed Name and
Signature of the HSC Chair __________________________ Date

IRB/RSCP Use Only

Project Number ___________________________________ Received RSCP

Sent to: __________________________________________ Date:

Final Status

9 Approved as Exempt under section 9.02 of the IRB Policies and Procedures (Cite reasons for exemption):

9 Approved as Expedited under Section 9.03 of the IRB Policies and Procedures because (Cite reasons for expedited status)

Printed Name and
Signature: __________________________________________ Date

IRB (for the Committee)

9 Approved by Full review under Section 9.04 of the IRB as meeting requirements of the IRB Policies and Procedures.

Printed Name and
Signature: __________________________________________ Date

IRB Chairperson

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Perceptions and Relationships with Optical Water Quality in Ozark Rivers
Amie West

Attachments:
1. Script
2. Information Card

1. Script

“Would you be willing to participate in this brief survey and activity as part of my dissertation research at the University of Arkansas? It should take less than ten minutes and no identifying information is requested. The written survey is 7 questions. You will then be asked to look at a series of photographs and organize them by any criteria you deem meaningful, and then describe your organization.”

2. Information card given to each potential participant.

This research aims to investigate how users of rivers in Northwest Arkansas perceive water quality and to gain information about how optical water quality is interpreted and valued. It will also investigate how these perceptions relate to established scientific parameters of water quality.

Participants will answer a brief written survey about their knowledge of river water quality and will be asked to organize a series of 20-30 photographs of rivers and to verbally describe their organizational priorities. Participation should take less than ten minutes.

Participation is voluntary. Refusal to participate will not adversely affect any other relationship with the University or the researchers (and/or any third party if applicable).

If you have any questions regarding this survey or how the results will be used, please contact Amie West at aowest@uark.edu.

Principle Researcher: Amie West

Faculty Advisors: Thad Scott, Justin Nolan

If you have any questions or concerns about your rights as a participant, please contact the University of Arkansas Institutional Review Board, Research Compliance:
109 MLKG Building
Fayetteville, AR 72701
IRB@uark.edu
479-575-2208

IRB #14-07-007
Approved: 08/07/2015
Expires: 07/13/2016
Perceptions and Relationships with Optical Water Quality in Ozark Rivers
Amie West

Attachments:
1. Script
2. Information Card
3. Survey
4. Materials (photographs)

1. Script

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