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PERCEPTION STUDIES TO DETERMINE RECEIVING-STREAM COLOR OBJECTIONABILITY DUE TO EFFLUENT DISCHARGE

by

Sarah Elisabeth Girdner

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Major: Civil Engineering

The University of Memphis

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PREFACE

The problem of determining objectionable color in a stream due to effluent contribution has a history dating back to 1968. The focus of this research was to develop a methodology that is transferable to other locations who struggle with remaining in compliance due to this color narrative and to provide recommendations to a wastewater facility in Memphis, TN to aid in permit compliance. The study combined photo simulation techniques, on-site perception visits, and environmental data collection to assign attributes to those photos used in simulations in an approach that combines engineering principles with psychology.

This research will be presented to the following journal article and has been included in Chapter 2 as this thesis:

Girdner, S., Waldron, B., Louwerse, M., and Ivey, S. “Perception studies to determine receiving-stream color objectionability due to effluent”. *To be submitted to the ASCE Journal of Environmental Engineering.*

I would like to thank my thesis committee members, Dr. Brian Waldron, Dr. Stephanie Ivey, and Dr. Max Louwerse for their continuous support, advice, and guidance throughout the duration of this project with a special thank you to Dr. Waldron for spending an enormous amount of time and effort with me to sift through issues that arose during this study.

ABSTRACT

Girdner, Sarah Elisabeth. M.S. The University of Memphis. December/2014. Perception studies to determine receiving-stream color objectionability due to effluent discharge. Major Professor: Dr. Brian Waldron.

The United States' Environmental Protection Agency (EPA) provides general water quality guidelines for recreational water use that are similar to recreational standards published throughout the world. These guidelines are enforced by State agencies. In the State of Tennessee, the Tennessee Department of Environment and Conservation (TDEC) is the permitting authority who oversees these water quality guidelines. It sets color limits for a recreational water use color narrative under the auspices of EPA review that requires effluent discharge to be free of objectionable color. However, the narrative lacks numeric guidance on how to determine an acceptable discharge color. The City of Memphis, Tennessee had concerns about the subjectivity of the narrative and initiated a color study to provide TDEC with recommendations to establish numeric limits for NPDES permit compliance. This color study links human perception of river color contrasts (subjective) with measured true and apparent color and environmental data (objective) in four experiments. In Experiment, participants visited three riverside locations once a month for a year and only one person noticed an objectionable color, while the remaining perceived color contrasts related to cloud/sky reflections. Experiments 2-4 recruited participants online through Amazon's Mechanical Turk (AMT). In Experiment 2 participants were asked to determine whether two colors of the color palette were different, while their choice and response time was recorded. In Experiments 3 and 4, this procedure was repeated, except that actual Mississippi River pictures taken throughout the year were used for the discrimination task. Results showed that environmental factors -- cloud cover (sky reflections) and seasonal leaf foliage -- overshadow effects the wastewater effluent color may have on perceived objectionable river color differences. Since an individual’s perception of objectionable color primarily is the result of environmental factors, suggesting a numeric color limit for NPDES permits in Memphis, TN is deemed unnecessary as these facilities have no control over these factors.

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Introduction

Recreational color narratives are found worldwide and require dischargers to take corrective action when the waste being discharged produces an objectionable color in the receiving stream. The color narrative found in water quality guidelines written by the Environmental Protection Agency (EPA) has existed for nearly 50 years without numeric limits or a proposed methodology to determine those limits leaving the narrative vague and subjective to human perception. Enforcing and adhering to the subjective narrative become difficult due as there is limited research exists on this topic, and the studies that do exist fail to determine when objectionable water color changes are perceived. The City of Memphis initiated a 'Color Study' after the Tennessee Department of Environment and Conservation (TDEC) and EPA asserted that they perceived an objectionable color discharging at one of the City's wastewater treatment facilities. Through the Color Study initiation the City of Memphis requested assistance from the University of Memphis Ground Water Institute to recommend color limits for the North Wastewater Treatment Facility's, M.C. Stiles, National Pollutant Discharge Elimination System (NPDES) permit. Though previous research failed to determine when objectionable color changes were perceived in the receiving stream, they were able to identify factors that alter perception of color and provide a general method that was improved upon in this study in a more comprehensive approach that can be applied anywhere. The goal of the study is to determine those factors that impact an individual's perception of objectionable color at the M.C. Stiles facility and potentially generate an algorithm that defines those numeric limits for the City of Memphis.

Perception studies to determine receiving-stream color objectionability due to effluent discharge

1. Introduction

Since the 1970s, the Environmental Protection Agency (EPA) has been developing recreational water quality criteria, similar to those found across the world (e.g., World Health Organization), as guidance for adopting water quality standards. *Quality Criteria for Water 1976* was one of the first reports compiled to provide narrative standards for over 50 pollutants, including color. The recommended color criteria specified that, “Waters shall be virtually free from substances producing objectionable color for aesthetic purposes…” (EPA 1976). National numeric limits on color were not set because ‘objectionable color’ is subjective and the natural background color of water is site dependent. States use the color criteria from the amended *Quality Criteria for Water 1986* report to adopt water quality standards (EPA 1986).

The Tennessee Department of Environment and Conservation (TDEC) *General Water Quality Criteria* for recreation, *Ch.* 0400-40-03-.03(4)(d) provides that there shall be no “total suspended solids, turbidity or color in such amounts or character that will result in any objectionable appearance to the water, considering the nature and location of the water” (TDEC 2013). No numeric limits have been provided.

The National Pollutant Discharge Elimination System (NPDES) permit program includes a similar narrative in the permits distributed to industrial and municipal direct dischargers. The NPDES permits for the Wastewater Treatment Plants (WWTPs) in Memphis, Tennessee state that “[t]he wastewater discharge must not cause an objectionable color contrast in the receiving stream" (City of Memphis 2012).

Both EPA and TDEC asserted that they observed an objectionable color contrast in the Mississippi River caused by the mixed effluent-river water from the City of Memphis' M.C. Stiles WWTP. Numeric effluent limits are not defined by the NPDES permit or TDEC's General Water Quality Criteria. As a result, the EPA, TDEC, and City of Memphis agreed to conduct a "Color Study" as part of a Consent Decree (CD) Case 2:10-cv-02083-SHM-dkv (2012) to help TDEC establish numeric limits for the M.C. Stiles WWTP.

Research on the perception of water color in the context of effluent discharge to receiving bodies of water is limited. In 1976, the National Council of the Paper Industry for Air and Stream Improvement (NCASI) performed a study to determine the ability of individuals to detect water color changes, but not whether or not those changes were objectionable (NCASI 1975). A total of eleven observers were selected to determine whether they could detect color increases or decreases at six study sites located in six states throughout the southern United States over an eight-week period. The study identified the following factors that alter one's perception of changes in water color: background water color, intensity of site lighting, direction of color change, magnitude of color change, participant differences, and participant background color memory. Psychological influences such as memory, confusion, and observer differences also played a role in one's perception of changes in water color.

In 1989, a color study was conducted on the Hiwassee River where the Bowater pulp and paper mill discharges to determine if color changes were detectable and whether or not those changes reduced the perceived attractiveness of the river (A.M. Prestrude and E.L. Laws, unpublished report, April 1989). Study participants rated colored water samples in jars, artificial streams, numerous images of the river, and made on-site observations from a boat. During on-site observations, water samples were taken and tested for apparent color. River imagery and on-site observations were conducted mid-day under similar lighting with intermittent cloud cover. The results of the study indicated that observers were able to discriminate water color differences with an increase of apparent water color yielding a decrease in attractiveness when water samples were viewed in jars or artificial streams. But when the water was viewed in context to its natural environment, results showed that lighting conditions, the river's background riverscape and water characteristics had more influence on perceived attractiveness of the environment than water color.

These previous studies have provided important factors that influence the perception of water color. However, they include small population sizes and the results are not transferable to other environmental settings. The methodologies of both studies fail to address when objectionable river-effluent water color is perceived *in-situ,* but provide methods that can be improved upon to determine when objectionable river-effluent color is perceived in the receiving stream. As part of the effort to provide meaningful data from which to establish numeric limits for the M.C Stiles WWTP, we aimed to develop an algorithm that estimated the extent to which a given water color is considered objectionable at the M.C. Stiles WWTP. The study extended the findings from previous studies by investigating to what extent water color is objectionable when a) the color is considered in isolation; b) the color is considered in combination with the Mississippi River scenery; c) the color is considered in combination with weather variables (wind, rain, etc.); and d) participants who are very familiar with the Mississippi River are compared with participants who are not familiar with the river.

2. Background

The City of Memphis is located in Shelby County, TN. The City owns and operates the M.C. Stiles WWTP, which treats 378,541 m^3/d (100 MGD) before discharging to the Mississippi River, as shown in Figure 1.

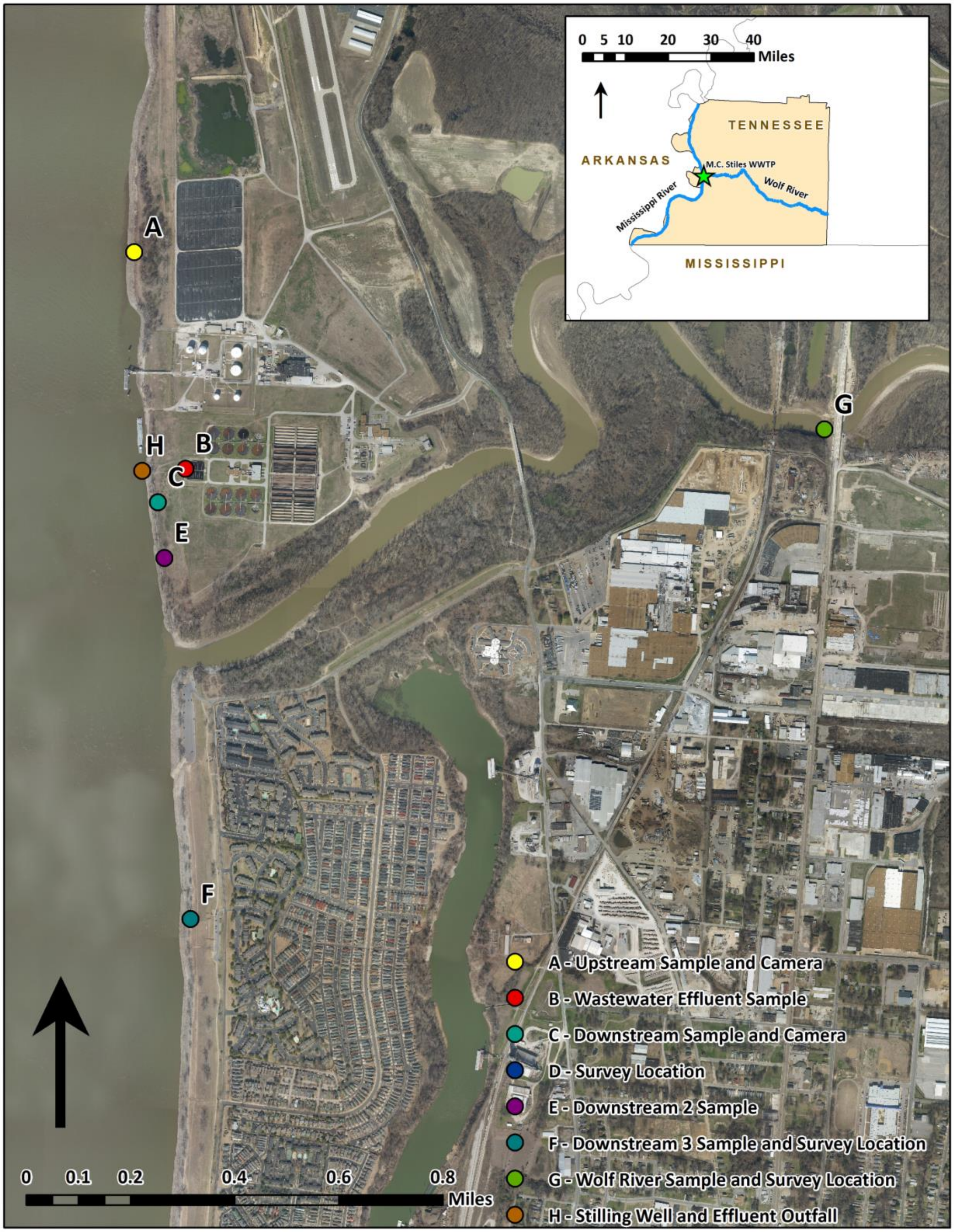

Figure 1. Study site locations for objective and subjective analyses.

Two industrial users, a pulp mill and a baker's yeast producer, contribute dark colored wastewater to the M.C. Stiles WWTP. The pulp mill produces cotton cellulose for 8 continuous days followed by a 6 day non-production period. The pulp mill generates an average of 20,063 m^3/d (5.30 MGD) of wastewater during pulp processing and an average of 2,763 m^3/d (0.73 MGD) during non-production cycles. The baker's yeast industry generates an average of 3,520 m^3/d (0.93 MGD). The dark colored wastewater flows from both industries directly to the M.C. Stiles WWTP without pretreatment. While Memphis' WWTP provides some treatment, colored wastewater may, nevertheless, be discharged to the Mississippi River.

The Mississippi River drainage basin includes all or parts of 31 states and two Canadian provinces and transports an average of 150 million tons of sediment annually in the lower Mississippi River (Thorne, et al. 2008). The U.S. Army Corps of Engineers (USACE) Memphis District is responsible for keeping the channel open for navigation by retaining a minimum 2.7 m (9-ft) deep and 91.4 m (300-ft) wide waterway (Division Bulletin No. 2 Navigation Conditions for 2011 2011). On average, the Mississippi River at Memphis, TN, is 0.80 km (0.5 mi) wide with a discharge between 447,723,325 m^3/d – 3,090,024,910 m^3/d (120,000 - 820,000 MGD) (US Army Corps of Engineers 2003).

The Wolf River is a tributary to the Mississippi River that traverses east to west across Shelby County, draining approximately 570 km^2 (220 mi^2) (28%) of the county. It converges with the Mississippi River approximately 600 m (0.4 mi) south (downstream) of the M.C. Stiles WWTP outfall and directly north of Harbor

Town, a residential area where recreation occurs on the riverbank (e.g., walking, jogging, and minimal fishing), on the Mississippi River (e.g., boating and some canoeing/kayaking), but rarely if ever in the river (e.g., swimming and water contact sports) due to hazardous conditions (e.g., powerful river flow, debris, and barge traffic). The only discharge gage on the Wolf River is at Germantown Road, approximately 30 km (18.6 miles) upstream from its confluence with the Mississippi River, but the Wolf is expected to gain in flow as it moves through the City. At the Germantown Road gage, the average discharge over the past six years (2007-2013) is 2,282,655 m^3/d (603 MGD) with a minimum and maximum flow of 433,044 m^3/d (114 MGD) and 70,706,033 m^3/d (18,681 MGD), respectively.

3. Objective Analysis: Environmental Data and Participant Surveys

In order to assess human perception of water color change, a series of participant surveys were conducted to ascertain their willingness to recreate alongside or in the water, their ability to recognize color variation from a control color, and the influence of environmental conditions on their decision of color similarity or dissimilarity. Integrated into the survey analyses on color similarity or dissimilarity were laboratory measurements on water color as derived from 54 water samples and environmental data collected on-site. It was anticipated that the surveys would indicate a defining set of conditions for when water was considered objectionable based on its color. The recreation-related participant survey involved on-site observations to three riverside locations and questions related to different recreation activities as well as perceived existing environmental conditions. The Amazon Mechanical Turk (AMT) survey platform was used for the remaining three participant surveys, each differing in development and deployment. AMT surveys are a well-accepted method for conducting psychological cognitive studies that provide a large random pool of respondents for minimal cost in a short period of time (Mason and Suri 2011). The environmental conditions that were incorporated into two of these three surveys were derived from data collected from instrumentation deployed on-site. Each participant survey, laboratory analyses and environmental condition data collection are discussed in greater detail in the sections that follow.

3.1. On-Site Environmental Data Collection

Over the period of a year, on-site instrumentation collected weather parameters, Mississippi River elevation, and images of the Mississippi River at a location upstream and downstream of the effluent outfall while water samples were collected and analyzed from six locations. Results from the Hiawassee and NCASI studies indicated that several of these environmental factors play a role in an individual's perception of water color change and attractiveness. River and effluent samples were collected once a week for a year for tri-stimulus and platinum-cobalt testing from the following 6 locations as shown in Figure 1: (1) upstream of the effluent outfall to act as the control color (Fig. 1A), (2) downstream of the effluent outfall for the immediate wastewater effluent impact (Fig. 1C), (3) location north of the Wolf River eddy and south of the first downstream location (Fig. 1E), (4) Wolf River at Highway 51 to avoid Mississippi River backflow (Fig. 1G), (5) Harbor Town, a residential area, where the Wolf River color contributes (Fig. 1F), and (6) effluent from the contact basin (Fig. 1B)These samples were used to assess the impact of wastewater effluent color on the Mississippi River at several locations downstream of the effluent outfall. We hypothesize that the impact of the effluent on river color will gradually decrease further downstream until the Wolf River confluence where the effluent will have virtually no impact on the Mississippi River at Harbor Town since the Wolf River at its minimum flow discharges more than the WWTP's effluent.

3.1.1. Water Sampling

Mississippi River, Wolf River, and wastewater effluent grab samples were collected every Wednesday morning from January 2013 - 2014 (n = 54) at the sampling sites shown in Figure 1. Samples were transported to the University of Memphis and analyzed on the same day using two methods: Platinum-Cobalt and tri-stimulus. Hach Method 8025 (Hach, 2013), modified to the NCASI procedure for Platinum-Cobalt which is a common standard for pulp and paper effluent, was used to analyze all samples for true and apparent color on a DR/2500 (Hach Company, Loveland, CO). Prior to this investigation, the City of Memphis wastewater laboratory conducted a study on the effects of pH on color and determined there was minimal impact and thus relaxed the pH requirement of 7.60 specified by Method 8025 to the range of 7.55 – 7.70. Prior to analysis, the collected samples were also adjusted to fall within this range. For tri-stimulus tests, undiluted samples for Fig. 1 A-C locations were also prepared using Method 8025-NCASI to analyze for true and apparent color on a Black Comet CXR SR (Stellar Net Inc., Tampa, FL) (StellarNet Inc., 2011). Tri-stimulus color values represent three-dimensional space by sampling over the light spectrum of 220 – 1100nm, and are provided as L*a*b* (lightness, red/green, and yellow/blue, respectively) (CIE 2004).

3.1.2. Environmental Conditions

Environmental conditions influence a person's perception of color (Hiwassee River Study 1989; NCASI 1975). Therefore, weather conditions, river stage and effluent discharge observations were collected over a one-year period from January 2013-2014. A Vantage Vue Wireless Weather Station (Davis Instruments, Hayward, CA) (Fig. 1B) recorded precipitation, wind speed and direction, and temperature every 15 min, while cloud ceiling data (i.e., overcast, broken, and clear) was provided by the Memphis International Airport (MIA) weather center located 11 mi (18 km) from the study site. Mississippi River stage was recorded from a stilling well installed along the bank using a Levelogger Gold 3001 F15/M5 (Solinst, Canada) on a 15-min interval. The pressure transducer was downloaded and redeployed weekly with stage corrections made to mean sea level by performing a survey from a benchmark set using an R8 survey-grade GPS unit (Trimble, Sunnyvale, CA), and corroborated with river stage recordings from the downstream Weather Bureau Gage (MS126). River stage readings were corrected for barometric pressure with a Barologger Gold 3001 F5/M1.5 (Solinst, Canada).

Trophy Cam 8 MP Trail Cameras (Bushnell Outdoor Products, Kansas City, MO) located upstream and downstream of the effluent outfall (Fig. 1A and C) were oriented due west to capture photos of the Mississippi River and the adjacent bank hourly for 12 h starting at 6 A.M. for one year to capture seasonal and lighting changes. The images had to be filtered to remove photos with blocked views of the river (e.g., barges and birds) and processed for use in psychological experiments.

3.1.3. Platinum-Cobalt Results

Partial correlations were performed by SPSS 21 (IBM Software, Armonk, NY) to analyze true and apparent color data, as shown in Table 1, for each sampling location (Fig. 1A, B, C, E, F, and G) controlling for upstream color[1], the natural background color of the river at this location.

Table 1. Apparent and True Color Unit Data for Each Sampling Location

	Sampling Location	Maximum (CU)	Minimum (CU)	Mean (CU)	Standard Deviation (CU)
Apparent Color	Upstream (A)	2698	142	717	523
	Effluent (B)	2910	261	1127	644
	Downstream (C)	2445	137	724	479
	Downstream 2 (E)	2487	128	683	468
	Wolf River (G)	3383	88	476	503
	Downstream 3 (F)	2458	108	699	504
True Color	Upstream (A)	108	7	30	21
	Effluent (B)	1005	58	443	308
	Downstream (C)	140	14	58	33
	Downstream 2 (E)	159	8	47	29
	Wolf River (G)	473	23	88	76
	Downstream 3 (F)	193	9	41	32

Effluent apparent color (Fig. 1B) is significantly related to the first downstream location (Fig. 1C), $r = .336$, $p = .017$, and second downstream location (Fig. 1E), $r = .381$, $p = .006$, but is not significantly related to the third downstream location (Fig. 1F) where the majority of recreation occurs along the river bank. The apparent color at the third downstream location (Fig. 1F) is significantly related to

[1] The minimum background color of the Mississippi River is 140 Color Units (CU) – this compared to the background colors of the two aforementioned studies: the Hiwassee River (40 CU) and the NCASI study (2-15 CU).

the apparent color of the Wolf River (Fig. 1G), $r = .307$, $p = .030$. Similar relationships exist for true color data. Effluent true color is significantly related to the first and second downstream locations, $r = .570$, $p < .001$, $r = .44$, $p = .001$, respectively, while the Wolf River true color is significantly related to location F, $r = .484$, $p <.001$. These correlations show that the color of the Wolf River has a greater impact on the color of the Mississippi River where recreation is prevalent (Fig. 1F) than the wastewater effluent.

3.2 Participant Surveys

To understand the factors that contribute to an individual's perception of environmental conditions *in-situ* and of color change *ex-situ* without other visual and physical stimuli interference, the University of Memphis' Psychology Department developed an on-site environmental condition questionnaire (Experiment 1) and a series of three of Amazon's Mechanical Turk (AMT) experiments (Experiments 2-4) using color swatches and river images. Perception of environmental conditions *in-situ* varies spatially and temporally. When the decision to recreate at a given location is made, personal preference for a desired activity is influenced by their perception of environmental conditions. Thus, the prediction for Experiment 1 was that the perception of environmental conditions was influenced by numerous factors which are eventually compounded to make recreational decisions with little weight given to any individual factor (including river color/ river color changes). For the AMT experiments, the prediction was that environmental factors may still influence the perception of water color change, but water color may impact perceived color changes. Statistical analyses were performed by SPSS 21.

3.2.1. Experiment 1

Experiment 1 asked a series of general environmental condition questions and then a series of recreational questions to determine which factors contribute to an individual's decision to recreate on or near a body of water – in this case the Mississippi River – and how individuals perceive river color/ river color contrasts.

3.2.1.1. Participants

Up to 15 participants from the University of Memphis were recruited monthly for a year (n=90). As indicated by self-report, the majority of participants were 21 and under (54%), with the remaining participants falling under the 22-25 (27%), 26-30 (9%), 31-40 (7%), and 41-50 (2%) age brackets. The length of time participants lived in Memphis ranged from 0 to 32 years (M = 14.48, SD = 9.22) and 47% were male.

3.2.1.2. Materials and Procedure

A questionnaire was developed that asked participants questions about their perception of their surroundings and their willingness to recreate at the survey site. To avoid priming participants on the purposes of the study, questions directly related to the objectionability of the water color were avoided and general questions about the color of the water and surrounding environment were asked instead. The survey was designed to incorporate open-ended responses and a rating scale. Participants rated the likelihood of recreation for various activities (e.g., kayaking, running, picnicking, swimming, and others) and commented on whether they would participate in that activity.

Participants were told they would visit three locations to record their assessment of the environment, and questionnaires were provided on-site to avoid priming participants about the location or purpose of the study. On-site surveys were conducted monthly from April 2013 - 2014. Each month, volunteers visited sites (Fig. 1D,F, and G) and answered questions pertaining to their observed surroundings as well as their interest in recreating there. Responses pertaining to river water color were categorized by whether a participant could detect a color change (multiple color response) or not (single color response) and whether river color impacted their decision to recreate.

3.2.1.3. Results

Out of 270 responses across the three survey sites, 206 (76.3%) participant responses detected a single river color, while 64 (23.7%) detected multiple colors which were primarily due to sky reflections with one individual who detected an 'orange-brown' color at the WWTP (–Fig. 1D) as shown in Table 2.

Table 2. Combined On-Site Participant Responses to River Color at Every Survey Location

Single Colors	Count	Multiple Colors	Count
Brown	150	Blue-brown[b]	31
Blue	27	Grey-brown[b]	11
Grey	25	White-brown[b]	4
Green	3	Orange-brown[a]	1
Tan	1	Other combinations[b]	17
Total	206	**Total**	64

[a] Color combination not related to sky reflection
[b] Color combination related to sky reflection

As indicated in Table 2, white, grey, and blue color combinations were deemed products of sky reflection as they are colors frequently detected due to sky reflections in turbid waters that are sediment-rich (Braun and Smirnov 1993; Lynch and Livingston 2001). When participants were asked if the color of the water was uniform/consistent, 11 people noted different ‘brown’ patches at the Wolf River (– Fig. 1G) and 1 person noted patches of ‘dark brown’ at the WWTP (Fig. 1D). In a few instances (n=6), participants made recreational decisions based on a single ‘brown’ river color; only one of the decisions was made at the WWTP. Overall, individuals did not notice a water color contrast or consider water color a major factor in their recreational decision criteria. As predicted, the majority of recreational decisions were based on other environmental conditions (e.g., insects, weather, personal safety (i.e., crime), and river current).

3.2.2. Experiment 2

In Experiment 2, participants were presented with two color swatches that included primary colors and a range of colors in-between to investigate the color deviation necessary between the color swatches for an individual to perceive a color contrast. Participants were asked whether the color stimuli were similar or dissimilar. Response time (RT) and response choice (RC) data were analyzed to determine whether individuals perceive gradual color changes or if there is a definite point at which color changes are perceived. The prediction being that there would be a definite point at which participants observe a color change.

3.2.2.1. Participants

A total of 694 participants were recruited through Amazon Mechanical Turk. Eligibility criteria for participation in each AMT experiment mandated that respondents reside in the United States, be validated members of AMT, and not be color-blind. RTs, demographics, and computer monitor specifications were recorded. As indicated by self-report, participant age ranged from 18 to 69 (M = 37.87, SD = 12.30) and 51% were male.

3.2.2.2. Materials and Procedure

Color swatches were derived in Adobe Photoshop CS6 by taking RGB values for primary colors and then taking color steps of 30 R/G/or B units to compose the remaining colors in-between green and blue, as show in Figure 2, for a total of 44 swatches.

Figure 2. Colors used in Experiment 2 to generate stimuli to determine color change perception.

Each color swatch was matched uniquely with another color swatch for a total of 932 color pairs with an additional 60 randomly selected stimuli duplicates shown side by side on a white background (1020 pixels tall by 700 pixels wide) as shown in Figure 3.

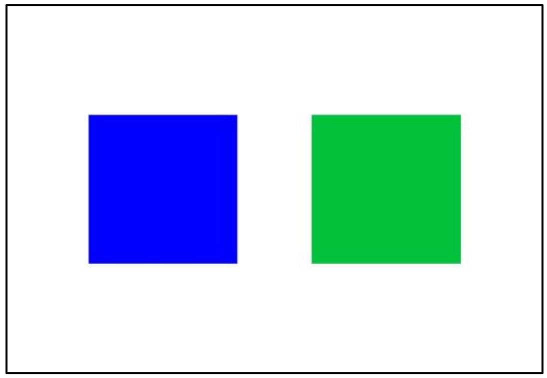

Figure 3. Example of stimuli rated by participants in Experiment 2.

Participants were asked to rate the color of each stimuli pair as ‘similar’ or ‘dissimilar’ – recorded as binary ‘0’s and ‘1’s, respectively - as quickly as they could. Before starting the survey, participants were asked to type the instructions in their own words for quality control. Then, two horizontal color swatches (a stimuli pair) were presented in tandem for the participant to rate with a 0.65 s lag between stimuli until all pairs were rated. To reduce the total survey time for participants, the survey was divided into four trials, each with 248 color pairs. Participant RCs and RTs were averaged and graphed with respect to the color step distance between color swatches in the stimuli pair.

3.2.2.3. Results

RT data and the corresponding RC data were filtered to exclude short RTs (<200 ms.) and long RTs (>5000 ms) before removing outliers with standard deviations greater than 2.5 times the mean (Whelan 2008; Baayen and Milin 2010). Five participants who either lived outside the United States or failed to complete RCs were excluded from all analyses. A total of 574 stimuli pairs were analyzed[2]. Of the 77,468 remaining responses, outliers were removed affecting 6.5% of the data.

Figure 4 shows a non-linear relationship between the average RC in relation to the color deviation of the stimuli pair being rated.

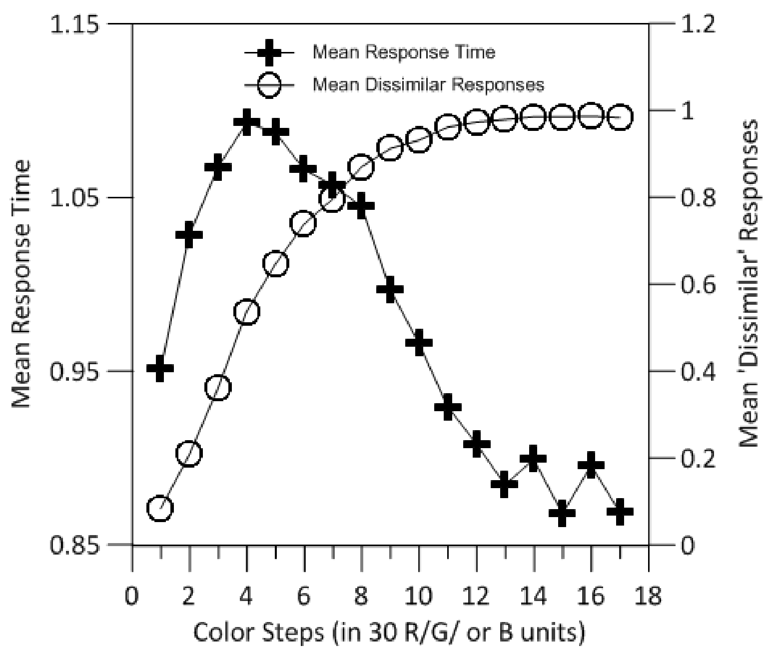

Figure 4. Results from Experiment 1 showing the average dissimilar responses has a slight sinusoidal curve showing that responses are not made arbitrarily and the average response time curve shows that it takes individuals longer to make 'similar' decisions and gradually becomes faster as obvious 'dissimilar' stimuli are shown.

By color step 4, 50% of participant responses were split showing that participants distinguished between 'similar' and 'dissimilar' colors. As colors became more dissimilar (i.e., higher color step), the curve becomes asymptotic at a mean

[2] Some stimuli did not conform to the R/G/ or B step distance and thus were excluded from the analysis.

dissimilar response of one. Participants agreed on ‘similar’ colors up to 4 color steps and ‘dissimilar’ colors after 6 to 8 color steps. The response time results show that ‘similar’ decisions up to 4 color steps become more difficult for participants to rate as the color deviation increases slightly. After 4 color steps, decisions become easier as the stimuli become increasingly ‘dissimilar’. The color steps between 4 and 6 to 8 are a difficult range for individuals to distinguish color differences.

3.2.3. Experiment 3

In Experiment 3, participants rated river images for similarity and the RCs were linked to environmental factors to determine which, if any, had an effect on river color perception. The Hiwassee and NCASI studies determined that seasonal changes and lighting conditions impact the perception of water color changes, so these factors were analyzed along with time of day to account for the position of the sun. The prediction for this experiment was that each condition would be significant with lighting conditions having the greatest significance on color change perception.

3.2.3.1. Participants

Experiment 2 eligibility criteria applied to Experiment 3, with a total of 240 participants. RTs, demographics, and computer monitor specifications were recorded for each survey participant. As indicated by self-report, participant age ranged from 18 to 82 (M = 36.03, SD = 11.84) and 50% were male.

3.2.3.2. Materials and Procedure

Three primary environmental conditions that impact water color perception were identified and assigned with two ‘extreme’ categories for a 2 x 2 x 2 design where each ‘2’ represents two conditions in each category, thus: (1) time of day (6:00-12:00 and 12:00-18:00); (2) cloud cover (clear and overcast); and (3) seasonal flora changes (leaves on and leaves off)[3]. Of the 8 bins (i.e., 2 x 2 x 2) generated from the environmental conditions, three downstream photos (Figure 1, location C) were selected for each bin. Each of the environmental conditions related to the stimuli pair were coded ‘0’ if the conditions were the same in both photos shown (e.g., overcast/overcast or clear/clear) or ‘1’ if the conditions were different (e.g., overcast/clear or clear/overcast). Each of the 24 downstream photos was matched with every other photo for a total of 276 stimuli pairs. The survey was split into two trials, each with 138 stimuli.

Experiment instructions and stimuli presentation were identical to those in Experiment 2.

3.2.3.3. Results

One participant took the survey outside the United States and was excluded from all analyses. The remaining outliers were removed as they were in Experiment 2. Of the 34,506 responses, 11.6% of the data required removal due extremely high, sporadic RTs which was likely due to server malfunctions that occurred.

The trials were analyzed using a mixed-effect regression analysis with time of day, cloud cover, and foliage as fixed factors and subjects fitted as random factors to account for the variance between subjects (Baayen, Davidson and

[3] The remaining two environmental conditions collected during this study, rain and wind, were excluded as primary variables. There were not enough rainy days to be statistically valid. The impact of wind on river color perception was captured with cloud cover.

Bates 2008). The model was fitted using restricted maximum likelihood estimation (REML) for RC. The final model shows both cloud cover, $F(1, 29447.88) = 3356.67$, $p < .001$, and leaf foliage, $F(1, 29452.37) = 175.32$, $p < .001$, significantly predicted RC[4]. Cloud cover, $t(29447.88) = -57.937$, $p < .001$, and leaf foliage, $t(29452.37) = -13.241$ $p < .001$, results show that participants are more likely to rate those stimuli pairs with the same environmental properties (e.g., overcast vs. overcast) as similar as compared to those with different properties (e.g., overcast vs. clear). As predicted, lighting changes impacted participant decisions more than seasonal leaf changes, but time of day was not significant. This suggests that the position of the sun and the glare it casts over the river does not impact an individual's perception of river color changes. Another mixed-effect regression analysis was run to relate RT to the factors in the prior model. Cloud cover, $F(1, 29440.63) = 119.81$, $p < .001$, and leaf foliage, $F(1, 29442.28) = 16.49$, $p < .001$, were significant predictors of RT. Cloud cover, $t(29440.63) = 10.946$, $p < .001$, and leaf foliage, $t(29442.28) = 4.061$, $p < .001$, results show that it took participants longer to rate those stimuli pairs with the same environmental properties as compared to those with different properties, which is consistent with the RT results from Experiment 2. Individual environmental parameters for each photo in the stimuli show that color change

[4] The same model was analyzed with a logistic regression mixed-effect model in SAS 93 (SAS, Cary, NC) . The results show that cloud cover, $F(1, 29318) = 2729.09$, $p < .001$, and leaf foliage, $F(1, 29318) = 173.06$, $p < .001$, are significant predictors of RC. Individuals are more likely to see 'dissimilar' water colors when cloud cover, $t(29318) = -52.24$, $p < .001$, and leaf foliage, $t(29318) = -13.16$, $p < .001$, for each photo are identical.

detection, or ‘dissimilar’ RCs, increases on overcast days and those months when leaf foliage is visible in the background of the photos as shown in Table 3.

Table 3. Crosstabs of Response Choice Predictors and Response Choice

Category	Parameters	Similar RC	Dissimilar RC	Total
Cloud Cover	Clear vs. Clear	4194	2855	7049
	Overcast vs. Overcast	2889	4231	7120
	Clear vs. Overcast	2927	12587	15514
Leaf Foliage	None vs. None	2790	4290	7080
	Foliage vs. Foliage	2373	4722	7095
	None vs. Foliage	4847	10661	15508
Total Per Category		10010	19673	29683

3.2.4. Experiment 4

To understand if water color impacts the perception of river color changes, Experiment 4 used river imagery that excluded the background flora and sky to understand the effects of apparent laboratory analyzed color data on the perception of river color on the water cropped images. Without the influence of those environmental factors that impact perception of water color, the prediction is that the downstream apparent color will have an impact on participant RCs.

3.2.4.1. Participants

Experiment 2 eligibility criteria applied to Experiment 4, with a total of 240 participants. RTs, demographics, and computer monitor specifications were recorded for each survey participant. As indicated by self-report, participant age ranged from 19 to 67 (M = 32.46, SD = 9.51) and 44% were male.

3.2.4.2. Materials and Procedure

To link perception of color change to laboratory measured color values, one morning (6:00 – 12:00) and one afternoon (12:00 – 18:00) downstream photo along with the corresponding upstream photos were randomly selected on days that water samples were taken and analyzed for a total of 79 photo pairs. The 24 photos from Experiment 3 were also added. Images were pre-processed in two ways: upstream images were color balanced to downstream images and downstream images were color balanced to upstream images using Adobe Photoshop CS6's color match tool. Stimuli were color match coded to represent how the stimuli were color matched. Color matching was performed to reduce the effects of glare and intrinsic differences between cameras. Reversing the color balancing order helped to remove order bias. Each photo was then cropped to limit the participant's field of view to focus solely on the water surface. In total, 103 photo pairs generated 206 stimuli that were split evenly into two trials. An additional photo ID was assigned to each of the four stimuli (2 photos in a day times the 2 image pre-processes) for each day to assist in removing variance caused by laboratory measured color value duplication across the four stimuli (photos).

Experiment instructions and stimuli presentation were identical to those in Experiment 2.

3.2.4.3. Results

After 28 mismatched photo pairs (56 stimuli) were removed, there were 150 stimuli available for analysis. From the remaining data, the outliers were removed as they were in Experiment 2. Of the 22,748 responses, outliers were removed affecting 6.2% of the data.

The trials were analyzed using a mixed-effect regression analysis with cloud cover (i.e., clear, cloudy, and overcast), time of day (i.e., 6:00-12:00 and 12:00-18:00), river elevation, and upstream, downstream and effluent apparent color (Figure 1 – A, B, and C) as fixed factors with subjects and the photo ID fitted as random factors to account for the variance between subjects and the variance between duplicated photos taken on the same day (Baayen, Davidson and Bates 2008). The model was fitted using REML for RC. The final model shows that cloud cover, $F(2, 9640.36) = 70.77$, $p < .001$ is the only significant predictor of RC[5]. Clear vs. overcast cloud coverage, $t(7978.86) = 9.79$, $p < .001$, and cloudy vs. overcast cloud coverage, $t(11465.90) = 9.47$, $p < .001$, results show that individuals perceive clear days more dissimilar than cloudy or overcast days. Of note, Experiment 4 was developed to examine the effect of apparent water color, not cloud cover, on RC; therefore, the significance of clouds (not the t direction) as a predictor of RC is important only to show that cloud cover overshadows any effect apparent water color may have on an individual's perception of water color contrast. The results contradict the initial prediction that downstream apparent color would be a significant factor in one's river color contrast decision. However,

[5] The same model was analyzed with a logistic regression mixed-effect model in SAS 93. The results show that cloud cover, $F(2, 18085) = 8.89$, $p < .001$, is the only significant predictor of RC.

prior research concluded that site lighting had the greatest impact on water color contrast perception and these results also show the magnitude of the effect of cloud cover on the perception of river color contrasts (Hiwassee River Study 1989; NCASI 1975).

To determine if color matching impacted upstream, downstream, and effluent apparent color for RC, the data was split on the color match code and the same mixed-effect regression analysis was performed. There was no significance for either color match group suggesting that the color match did not impact how individual's perceived apparent color in the stimuli.

4. Conclusions

A color study was conducted to help establish when mixed effluent-river color may be perceived as objectionable. This study links human perception of river color contrasts (subjective) with measured true and apparent color and environmental data (objective) through four psychological Experiments. Experiment 1 involved participants (n = 90) visiting three riverside locations once a month to determine which factors impact recreational decisions as well as identify any objectionable water color contrasts. Only one person noticed an objectionable river color, while none of the participants made a recreational decision related to objectionable river color. Experiments 2-4 were conducted using Amazon's Mechanical Turk (AMT). Experiment 2 found color to be similar up to 4 color steps from the control and dissimilar, thus objectionable, after 6 to 8 color steps, following a non-linear response. Experiments 2 and 3 investigated the influence of environmental conditions and color (true and apparent) on perceived color differences through participant responses (similar versus dissimilar). Statistical analyses for Experiments 3 and 4 reveal that color objectionability, or dissimilar responses, was attributed to cloud cover and seasonal leaf foliage, and not related with the color values of analyzed water samples. Since perceived objectionable color is the result of sky reflectivity (cloud cover) and surrounding flora (seasonal leaf changes), suggesting a numeric color limit for the Memphis M.C. Stiles' NPDES permit is unnecessary as this facility has no control over these environmental factors. This methodology may be transferred to other effluent-receiving water bodies. For future studies, it is recommended that Platinum-Cobalt color units be measured more frequently at the upstream, downstream and effluent locations for a more robust statistical analysis.

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CONCLUSION

Recreational color narratives are found in water quality guidelines throughout the world. These narratives are difficult to enforce because numeric limits are missing since objectionable color is dependent on human perception and site characteristics. The City of Memphis in Memphis, TN, approached the University of Memphis Ground Water Institute to provide recommendations for when the north wastewater treatment facility, M.C. Stiles facility, may need to treat their effluent for color as this facility receives dark colored waste from two local industries.

This study combined civil engineering principles with psychology to address human perception of objectionable color with a comprehensive approach that is transferable at any location. To collect those environmental data that may impact color change perception, a weather station, stilling well, and wildlife cameras collected data for a year on the wastewater facility's property and water samples were collected and analyzed weekly for a year. The data collected was linked to the river imagery taken with the wildlife cameras to generate stimuli for surveys pushed out with Amazon's Mechanical Turk service, which is ideal for collecting a large random pool of participants. Three AMT surveys (Experiments 2-4) were generated in addition to an on-site survey (Experiment 1) to determine those factors that impact perception of river color change with and without visual and physical stimuli encountered on-site.

Experiment 1 involved participants (n=90) visiting three riverside locations once a month for a year to determine those factors that impact perception of river color change and that impact recreational decisions. The results showed that only one individual out of 90 noticed an objectionable color while several others noticed multiple river colors due to the reflection of the sky, but no one made a recreational decision based off of an objectionable river color. Instead, recreational decisions were based off of numerous environmental factors including safety, weather, and personal preference towards an activity. While Experiment 1 was conducted every month, Experiment 2 was developed to determine the color deviation between two colors before individual's perceived a color change and determined that colors are similar up to 4 color steps and are dissimilar / objectionable after 6 to 8 color steps, following a non-linear response. The results from Experiments 3 and 4 show that Mississippi River color change judgments are based off of cloud conditions and leaf foliage rather than apparent river color, which suggests that the effluent-Mississippi River apparent color mix was not significantly higher than the background color of the Mississippi River. Since objectionable color changes are perceived under certain cloud conditions and background foliage changes, suggesting a numeric limit for the City of Memphis M.C. Stiles wastewater treatment plant is unnecessary as this facility has no control over these environmental factors.