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What's It Worth? Estimating the Potential Value of Early Warnings of Cyanobacterial Harmful Algal Blooms for Managing Freshwater Reservoirs in Kansas, United States

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Cyanobacterial blooms are an issue drawing increasing concern in freshwater lakes and reservoirs in the United States due to the real and sometimes perceived harms they can cause through cyanotoxin production or other effects. These types of blooms are often referred to as cyanobacterial harmful algal blooms (cyanoHABs). Cyanotoxin exposure can potentially lead to human health effects through recreation and consumption of drinking water and may impact fisheries, wildlife, domestic pets, and livestock. Characterizing the societal impacts of cyanotoxin production, exposure, and effects and estimating the potential value of information of an early warning system can inform and support freshwater lake and reservoir management decisions and future research directions. A Bayesian decision tree analysis was utilized to identify uses, users, and benefits of the information provided by this research. Specifically, the potential value related to a cyanoHAB early warning system, based on potential toxicity, was analyzed that would provide information two additional days earlier relative to cyanoHAB toxicity. The evaluation considers the application of this information for freshwater lake management - whether or not to post an advisory or warning to avoid recreational water contact. The model was parameterized with data from the state of Kansas and the value of avoided foregone recreation and avoided health effects was derived. The estimated annual value of information ranges between $565 thousand to $2.3 million (2018 United States Dollars (USD)) for the state of Kansas alone based on provided assumptions. The results demonstrate a lower bound of the value of a cyanoHAB early warning system and suggest additional research to understand how the use and value of this information could support research prioritization and further illustrate the return on research investment. This analysis does not incorporate the full suite of potential societal costs that may be associated with a cyanoHAB event such as drinking water treatment, impacts to irrigation, or power generation.

Keywords: value of information, cyanobacteria harmful algal blooms, economics, decision tree, freshwater water quality

INTRODUCTION

Thick accumulations (typically nearshore) of cyanobacteria are a human and animal health concern globally due to a range of consequences that include cyanobacterial toxin (cyanotoxin) exposure, food web impacts, and aesthetics. Collectively, this phenomenon is often described as a cyanobacterial harmful algal bloom (cyanoHAB) when a designated real or perceived harm can be attributed to a bloom. Of particular interest are the potential harms associated with exposure to cyanotoxins. The harms attributed to cyanotoxin exposure include impacts on human health through recreation and consumption of drinking water. Additionally, cyanotoxins can impact fisheries, wildlife, domestic pets, and livestock. Other potential harms associated with cyanoHABs include food web issues, the presence of taste-and-odor compounds (no known adverse human health impact), increased oxidant demand and disinfection by-product formation (known adverse human health impacts), increased drinking water treatment requirements along with impacts to property values, fisheries, wildlife, domestic pets, livestock, tourism, and recreational opportunities. Each of these impacts has an economic implication. Cyanotoxin exposure that leads to health effects is a concern with global implications leading most U.S. States and some U.S. federal agencies to have event-response programs or health advisory guidance used to provide health protection due to consumption of finished drinking water and recreational contact (Chorus, 2012). The U.S. Geological Survey (USGS), along with partner agencies and others, is engaged in research activities that support the management of cyanoHABs which potentially reduces the societal and economic impacts of cyanoHAB incidents. Evaluating the magnitude of economic impacts of cyanoHABs and the value that additional information could provide for management decisions can support research prioritization and help researchers understand the use and value of their research. This paper documents a case study on the potential value of a cyanoHAB early warning system as applied to freshwater lake management in the state of Kansas, United States. It provides a framework that links cyanoHAB science to users, uses, and decisions and a methodology for valuing the potential benefits that additional information provides.

The state of Kansas is predominantly known as an agricultural state with nearly 3 million residents, approximately 21.2 million hectares of land mostly devoted to row crop agriculture and pastureland for livestock (U.S. Census Bureau, 2021). Most lakes in Kansas are reservoirs or impoundments (hereinafter referred to as lakes). There are 24 federal lakes operated by the Bureau of Reclamation and the U.S. Army Corps of Engineers, with most having state managed parks and refuges associated with these lakes (Kansas Water Office, 2015). The Kansas Department of Wildlife, Parks and Tourism owns and operates 40 state fishing lakes and local jurisdictions and has several community lakes as well (Kansas Department of Wildlife and Parks, 2021). Kansas relies on surface water as a drinking water source predominately in the central and eastern portion of the state with ground water becoming more prevalent in the western portion of the state. The state is a hunting destination and has a number of well-maintained fisheries.

Toxin-producing cyanobacteria blooms have been occurring in lakes across Kansas with some frequency. Kansas has been monitoring cyanobacteria or cyanotoxins since approximately 1990 and conducting a formal event-response program for cyanobacteria and/or cyanotoxins since 2010 (Trevino-Garrison et al., 2015; Kansas Department of Health and Environment, 2021). The program was developed out of a need for what appeared to be an increasing potential for adverse health outcomes due to cyanotoxin exposure in humans and companion animals with recognized effects on livestock in typically private waters outside of the jurisdiction of the Kansas Department of Health and Environment (KDHE). In 2006, a targeted nearshore bloom study was conducted by USGS in five Kansas lakes as part of a midwestern reconnaissance that showed multiple microcystin (the most commonly occurring cyanotoxin worldwide) congeners were common in sampled lakes, and multiple classes of toxins were also observed (Graham et al., 2012). A non-bloom targeted study conducted in 2007 (National Lakes Assessment), evaluated 27 Kansas lakes (Loftin et al., 2016). Approximately 15% of sampled lakes had detectable microcystins, saxitoxins, or both (anatoxin and cylindrospermopsin were not detected) (Loftin et al., 2016). Longer term monitoring studies on Cheney and Milford Reservoirs have shown consistent cyanobacteria bloom events nearly annually with variable spatial extent, frequency, and magnitude (Foster et al., 2017; Graham et al., 2017; Foster et al., 2019; Leiker et al., 2021).

Potential illnesses associated with cyanotoxin exposure typically go unreported. and information is not systematically collected or reported across the United States at this time (2021). However, data are available from Kansas in 2011 when 38 lakes reportedly had ongoing cyanobacteria blooms, 20 of which were categorized as an elevated risk posture with detectable or elevated cyanotoxins present. There was a total of 25 potential human exposure cases reported in Kansas during 2011; one case was categorized as suspected exposure, five cases as probable, seven confirmed human exposure cases, and two of those cases required continued hospitalization (Trevino-Garrison et al., 2015). Symptoms were mostly respiratory in nature, but there were also reports of eye irritation, rashes, and gastrointestinal issues in one case. Exposure activities included fishing, swimming, water skiing, jet skiing and knee boarding. There were seven reported exposure cases for domestic canines during the same time period with one suspected exposure case, one confirmed illness, and five cases were confirmed death due to exposure. Symptoms included vomiting, lethargy, weakness, liver failure and renal failure where necrosis was observed upon necropsy. Reports of canine illness and mortality associated with cyanobacteria and cyanotoxin exposure occur most years in Kansas (van der Mewre et al., 2012; Trevino-Garrison et al., 2015). Several animal and human exposures were noted in or around Milford Lake, a U.S. Army Corps of Engineers reservoir near Junction City, Kansas which had a particularly severe year on record with microcystin concentrations measured up to 150,000 μg/L (Graham et al., 2012; van der Mewre et al., 2012; Trevino-Garrison et al., 2015).

The state of Kansas was selected as a case study given its history of cyanobacteria blooms and cyanotoxin production in its lakes, active state event-response program for a number of years, and ongoing collaborations with USGS and other Federal Partners (Graham et al., 2012; Schaeffer et al., 2015; Trevino-Garrison et al., 2015; Loftin et al., 2016; Graham et al., 2017; Foster et al., 2019; Papenfus et al., 2020; Leiker et al., 2021; Smith et al., 2021). Given that it is still not understood when or why cyanobacteria produce cyanotoxins, early warning of toxic blooms above thresholds of concern for human health is critical for helping agency response efforts to be more timely to successfully minimize exposure events. Currently a range of approaches are used to identify potentially harmful scenarios that may result in cyanotoxin exposure, including direct cyanotoxin measurement or surrogate measures of cyanotoxins such as cyanobacteria cell abundance or algal pigment concentrations (e.g., chlorophyll-a or phycocyanin) (Chorus, 1999; Loftin et al., 2016; Stumpf et al., 2016). Eutrophication is often a factor in cyanoHAB occurrence; in the United States eutrophication is the primary cause of freshwater impairment (Selman and Greenhalgh, 2010). Previous studies have estimated the cost of anthropogenic eutrophication at $2.2 billion dollars per year (Dodds et al., 2009). This estimate provides an indication of the magnitude of costs; however, large assumptions were made and the actual costs in a given region remain unknown. Focused, regional analyses would increase the precision of estimates of economic damages associated with cyanoHABs. USGS provides scientific information to help managers consider impacts and select, implement, and evaluate best management practices to manage, mitigate, and reduce the effects of cyanoHABs. Evaluating the role of cyanoHABs information including the scientific basis that leads to an early warning system can support decisions on where to target data collection and research. The objective of this research was to assess the potential value of a hypothetical cyanoHAB early warning system which incorporates USGS and other science agency's information for a single application in a single state: management of freshwater lake closures for Kansas. This is a small, pilot-scale study to demonstrate the approach, describe the value narrative, and estimate the scale of benefits associated with a cyanoHAB early warning system.

For this pilot study, the focus is on early detection of cyanotoxin production during a cyanoHAB. As part of an interagency effort entitled Cyanobacteria Assessment Network (CyAN), the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and USGS are collaborating on the potential for using satellite data to develop an early warning system for cyanoHABs (Schaeffer et al., 2015). An early warning system could provide useful data in terms of "seeing" a cyanoHAB before it is otherwise identified; for the purpose of the current study, we focus on an early warning system that provides information on whether a cyanoHAB is producing cyanotoxins.

The cyanoHAB information has value to each of its users; however, the value has not been previously quantified. Unlike products and services that are traded in markets, federal agency data is provided free of charge and the value of information (VOI) can only be estimated using nonmarket valuation techniques. VOI has been a subject of interest for many years and in many different applications. A few of the most significant are the value of weather information, geospatial data, and natural disaster occurrence; each of these having very diverse sets of users and uses. A great deal of foundational research on the VOI was focused on the use of weather information for agriculture production and management as reported by Lave (1963), Johnson and Holt (1986), Sonka et al. (1987), Babcock (1990), Adams et al. (1995), Pielke (1995), Nordhaus and Popp (1997), and Hersh and Wernstedt (2001). The National Aeronautics and Space Administration (NASA, 2013) developed a primer on measuring the socioeconomic impacts of earth observations which documents varying approaches to valuing scientific information.

This study employs a Bayesian analysis decision tree approach to derive the VOI associated with a cyanoHAB early warning system. Other common approaches to estimating the VOI include evaluation of output or productivity gains, hedonic techniques, and stated preference approaches (i.e., contingent valuation) (Macauley, 2005). The decision tree approach is focused on a specific application of the information product in a real or hypothetical decision context, i.e., the use of cyanoHAB information as it informs freshwater lake closures, the influence of the information on management actions, the change in outcomes, and the marginal value of human welfare changes expressed in monetary terms as related to the additional information.

MATERIALS AND METHODS

Federal agencies provide research and laboratory services to users including state health and environmental departments, drinking water facilities, and others. An early warning system would benefit these users. When a potentially toxic cyanoHAB is suspected, water samples are sent to a laboratory for testing to determine levels of microcystin (and/or other toxins). An early warning system could be used by municipal water managers to enhance treatment processes, by natural resource managers to make decisions on freshwater beach closures, by private boating tour guides on switching of locations, and by the public on decisions where to recreate, among others. To evaluate the marginal benefit of an early warning system, a set of assumptions are determined and parameterized using a Bayesian decision tree; observations from the state of Kansas on previous incidents of cyanoHABs and cyanotoxins are used to populate the analytical model. A Bayesian approach to benefit estimation is a conventional statistical approach used to determine the VOI to dispel uncertainty in decision-making based on people's change in behavior when provided with new information. A Bayesian approach captures the full benefits of the data including direct, indirect, and ancillary benefits (Macauley, 2005).

A Bayesian decision tree approach conceptualizes the types of decisions, the alternative decision pathways, associated outcomes,

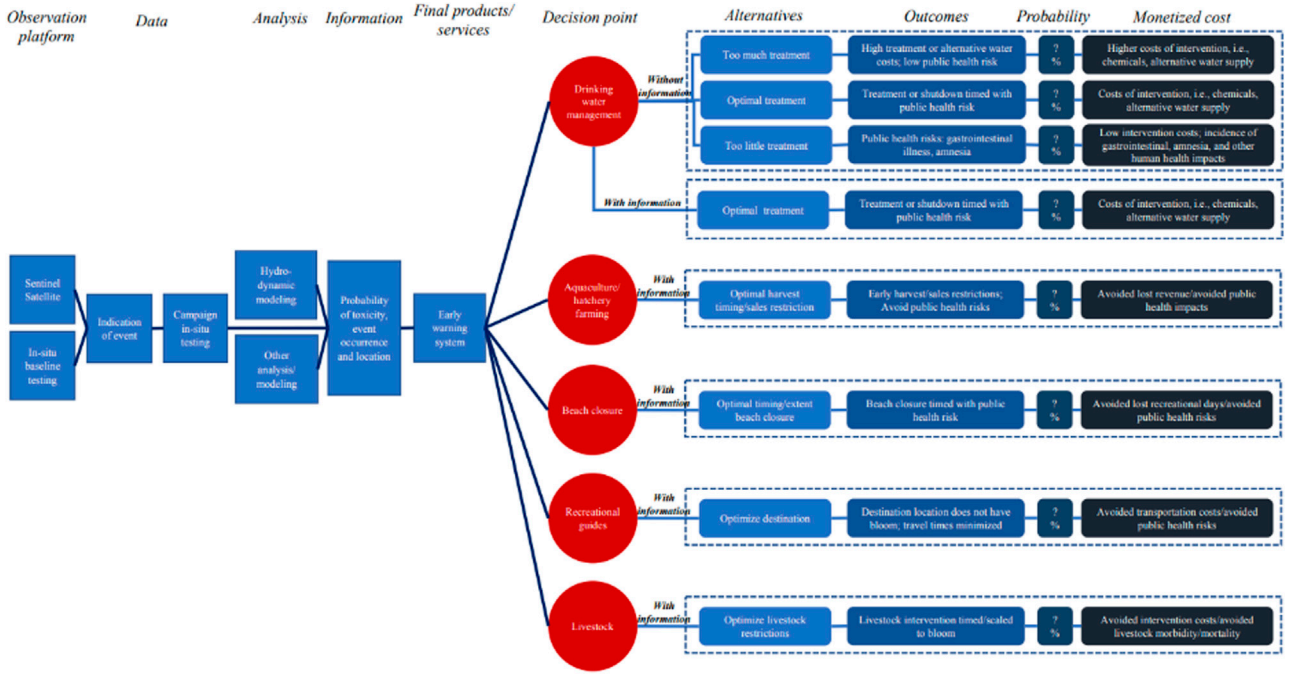

FIGURE 1 | Conceptual cyanobacteria harmful algal bloom value chain and decision tree. From Pearlman et al. (2019) public domain.

and monetized costs (see Pearlman and others, 2019 for use of decision trees). The approach relies on decision pathways under assumptions of with and without information. The without information is frequently referred to as the counterfactual scenario. Consistent with economic theory, the VOI is the marginal monetized benefits of the outcome with information and the outcome of the counterfactual scenario. The counterfactual is comprised of the next best information; the information that would have been used in the absence of the information being considered provides the most realistic estimate of the VOI whereas anticipating there is no information is likely to result in an overestimate of the VOI. To derive the total VOI, one would have to consider all of the decision points using the information, estimate the probability of decision pathways with and without information, and monetize the benefits of each decision pathway. If this is possible, the total VOI can be calculated as the difference between the monetized value of the outcome with data pathway and the sum of the weighted monetized values of the outcomes without data. This study is limited to a single decision application of the cyanoHAB early warning system, which represents a lower bound of the total VOI.

A decision tree was developed to conceptualize the many decisions and users that might be influenced by a cyanoHAB early warning system. At a workshop on the value of earth observation information (GEOValue) in October of 2017, a small group of experts on valuing scientific information and scientists, managers, and economists working in the cyanoHAB sphere developed a conceptual decision tree (Pearlman et al., 2019). **Figure 1** displays this decision tree, which is the basis for the current, more focused study. On the left of the decision tree, a value chain is shown. This is the supply chain for the information that influences decisions, i.e., what is the observation platform and how is the data transformed to information that is then used in a decision. It is important to note that this study values the whole "information product" rather than a specific data point that informs the early warning system. The conceptual decision tree shows the set of decisions and users that would use a cyanoHAB early warning system including drinking water managers, aquaculture farmers, lake managers, recreational guides, and livestock owners as identified at the workshop.

Beginning with the high-level decision tree, a more detailed decision tree relevant for the freshwater lake closure decision branch was developed for this study. **Figure 2** shows this decision tree (original figure developed in this study). The decision tree is intended to consider the hypothetical "with information" and the counterfactual "without information" to derive the benefit of the additional information that would be provided by a cyanoHAB early warning system. It should be noted that the outcome pathways are based on whether or not a cyanoHAB is producing cyanotoxins which influences outcomes and management actions (i.e., closing a beach to avoid health effects associated with a toxic event is likely, while a non-toxic cyanoHAB would not have the same set of risks). The decision tree, and analysis, simplifies the decision process and potential decision pathways to make it tractable while still being grounded in reality. The decision tree has three potential decision pathways: a freshwater beach is closed too soon, it is closed with optimal timing, or it is closed too late. The decision tree shows the qualitative outcomes and the approaches to monetize the effects.

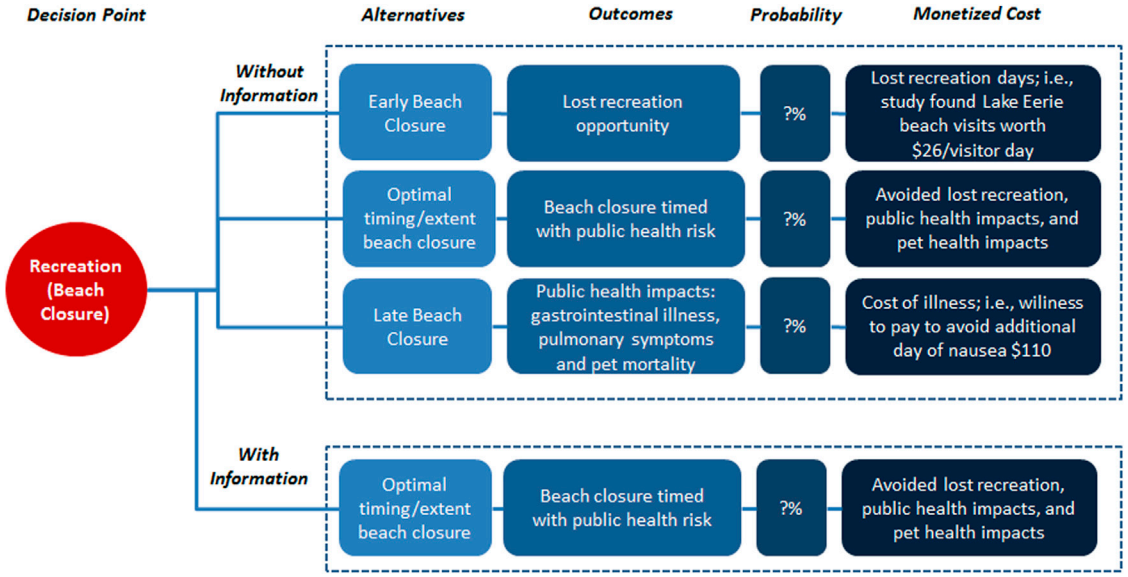

FIGURE 2 | Recreational beach management application of cyanobacteria harmful algal bloom information decision tree.

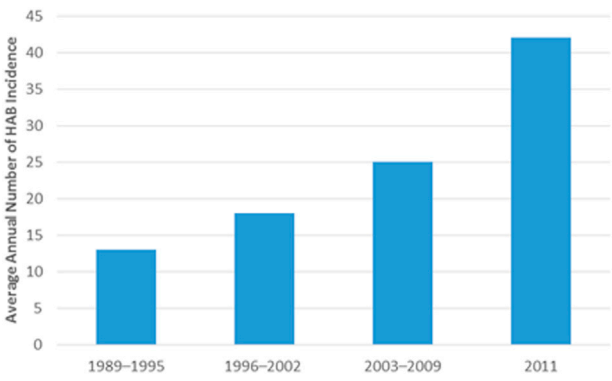

FIGURE 3 | Incidence of harmful algal blooms reported in Kansas (1989–2011) (data from Trevino-Garrison et al., 2015).

To determine a value associated with the incremental benefits provided by a cyanoHAB early warning system, the conceptual decision tree was parameterized using data from the state of Kansas. Incidents of suspected cyanoHABs are increasing in Kansas (see **Figure 3**, Trevino-Garrison et al., 2015). The Kansas Department of Health and Environment (KDHE) initiated a policy and response program for cyanoHABs in 2010. Prior to 2010, testing and action were not regularly undertaken. Under the policy change, testing for cyanobacterial cell counts is required if an animal or human illness is reported. Data on incidence in Kansas were available to support a what-if analysis of the availability of an early warning system. Two major benefit categories were considered: avoided recreation losses associated with closing a beach too soon (or at all) and the avoided health effects associated with closing a beach too late (or at all). Specifically, using the next best information and closing the freshwater lake because of a reported illness could lead to managers closing a beach when it is later determined through laboratory analyses that there is no threat posed to human health (i.e., microcystin levels are in fact below the threshold or concern or cyanotoxins toxins are not being produced and the reported illness was unrelated). Alternatively, a cyanotoxin event could be occurring prior to a reported illness and additional (unreported) incidence could be occurring prior to beach closure. The quantification required estimation of the incidence of toxic cyanoHAB events, recreational visitation, expected health effects, probability of decision pathways, and monetization of recreation and health effects. Details and assumptions of the quantitative analysis are documented next.

Incidence

Data for evaluating cyanoHABs incident frequencies were obtained from the Kansas Department of Health and Environment Division of Environment in 2018 (see https://www.kdhe.ks.gov/, 2018). Incidence is defined as a unique occurrence of a cyanoHAB, distinct incidence may occur in different parts of the same lake, at different times in the same lake, or in different lakes. In 2018, 39 water bodies in the state of Kansas were suspected of cyanoHABs (based on a human or animal illness). Of these, 32 lakes were confirmed positive based on cyanobacterial cell counts. It should be noted that this does not imply that a bloom is toxic (measured by the cyanotoxin microcystin). KDHE reported that in 2015 40% of all advisories were above the microcystin threshold while 59 out of 99 (60%) of weekly sampling events indicated that cyanoHABs were negative for microcystin. These data were used to estimate the probability associated with whether or not a cyanoHAB is toxic (it should be noted that a cyanoHAB may have effects not associated with cyanotoxins such as taste and odor, excessive biomass and/or low dissolved oxygen–the current analysis

focuses on the effects of cyanotoxins and therefore are primarily concerned with the toxicity of a cyanoHAB). Reported 2018 incidents were considered—39; with additional information it is assumed that closure of freshwater lakes in 7 of the incidents are avoided and that 40% of the 32 that are confirmed are toxic (13). This conservatively assumes the early warning system indicates toxicity indicators that would lead to advisories/closures with associated benefits but does not attribute health effects avoided for the 60% of assumed high cell count incidence that are not likely to be toxic.

Days of Avoided Effects

The next step is to estimate the duration of time that unnecessary closures or exposure would be avoided due to additional information. Two additional days are assumed of early warning which constitutes the marginal benefit of a satellite-based system. For lost recreation opportunities, the early warning system would provide two additional days of knowledge that the cyanoHABs are not toxic for seven water bodies. For health effects, there are 13 toxic events multiplied by two days, which equates to a gross exposure period of 26 days that are avoided because of the early warning system.

Avoided Recreational Losses

To assess the recreational losses from freshwater beaches being closed when it is not necessary (i.e., a non-toxic bloom), the likelihood of this to occur, data on freshwater beach visitation, and people's willingness to pay (the standard welfare measure) for beach visitation are needed. Data from the U.S. Army Corps of Engineers, Institute for Water Resources (2018) was used as the basis for estimating freshwater beach visitation. The data provide total annual visitation for 17 lakes managed by the U.S. Army Corps of Engineers in Kansas. Unique visits per day was calculated from the total annual median number of visitors to freshwater lakes per year divided by the number of days in the lake-going season. This yielded a minimum estimate of 1,024 visits per day assuming visitation is nearly year-round (360 days) and a maximum estimate of 4,099 visits assuming visitation is primarily during the summer (90 days).

Not all people that were planning to recreate at a freshwater beach would be deterred completely by a cyanoHAB related closure; rather, there are substitute locations that could alternatively be visited. To account for this, a substitutability factor is employed. The value was derived from a study of beach substitution as a result of cyanoHABs in Florida (University of Florida, 2016). The researchers found 16% of those surveyed would go to an alternative location if a cyanoHAB warning were issued. Therefore, the foregone visitation is 84% of what it would be without substitution.

The value of a unique visit to a freshwater beach was estimated using benefits transfer. A value in the state of Kansas was not identified in the literature; therefore, a study of day trips to Lake Erie in Ohio provided a proxy. Sohngen et al. (1999) estimated willingness to pay for a day trip to Lake Erie at $15.50 per visitor in 1997 USD; this value was escalated to current (2018) USD as $24.26 per visit.

Avoided Health Effects

To assess the societal value of health effects from freshwater beaches not being closed when it is necessary (i.e., a cyanoHAB is toxic), the likelihood of this to occur, data on freshwater beach visitation, health effects and relative risk, and people's willingness to pay to avoid a health effect are needed. In this case there are 13 incidents when there is an indication of a cyanoHAB and testing reveals that the cyanoHAB is producing cyanotoxins at levels of concern.

The data described above for number of visitors that visit freshwater beaches in Kansas are used for the health effects analysis. However, not all of the visitors will stay at the beach, enter the water, or otherwise recreate if there is a visible cyanoHAB even though there is not a warning or beach closure, reducing the number of people potentially exposed to cyanotoxins. Based on the University of Florida (2016) study, 50% of visitors would avoid a beach if there were a visible cyanoHAB.

There are multiple health effects related to exposure to toxic cyanoHABs from both direct ingestion (either through municipal water supplies or accidental ingestion during recreation) and skin exposure during recreation. It is unlikely for a toxic cyanoHAB to be lethal to humans; reported health effects include "abdominal pain, nausea, vomiting, diarrhea, sore throat, dry cough, headache, blistering of the mouth, atypical pneumonia and elevated liver enzymes in the serum" (Carmichael, 2001). For this analysis, a general gastrointestinal illness was used as the focus of the evaluation for health effects avoided. Not all people exposed to cyanotoxins *via* recreation will develop an illness. Known as the cumulative relative risk, the probability of a person developing an illness when exposed to a toxic cyanoHAB is not well documented. Stewart et al. (2006) estimated that the cumulative relative risk for those exposed to cyanoHAB toxins *via* recreation is 5%. This is the assumption used to derive the number of visitors expected to experience gastrointestinal illness (i.e., of those that recreate only 5% will develop an illness).

The value of avoiding a gastrointestinal illness was determined using benefits transfer. Mauskopf and French (1991) estimated willingness to pay to avoid an incidence of gastrointestinal illness at $222 in 1991 USD; this value was escalated to current (2018) USD as $410 per avoided illness (per person).

RESULTS

The results of this analysis indicate a positive economic value associated with two additional days of information as provided by a cyanoHAB early warning system. For avoided recreation losses due to the information, values range from $292,000 to $1.2 million per year in the state of Kansas. **Table 1** below summarizes the steps to calculate these results.

For those incidents that the toxicity of a cyanoHAB event could be determined sooner due to an early warning system, results indicate the value of avoided health effects (GI symptoms) range from $272 thousand to $1.1 million per year for the state of Kansas. **Table 2** below summarizes the steps to calculate these results.

TABLE 1 | Avoided recreational losses from cyanobacteria harmful algal bloom information.

Number of lakes/ Incidents	Additional Information (days)	Average dailyvisitation		Substitutablity factor	Avoided foregone Visitation		Value of a freshwater beach day	Avoided potential cost of foregone vistitation	
		Min	Max		Min	Max		Min	Max
7	2	1,024	4,099	0.84	12,042	48,204	$292.145	$24.26	$1.169.435

TABLE 2 | Avoided health effects from cyanobacteria harmful algal bloom information.

Number of lakes/ Incidents	Additional Information (days)	Average dailyvisitation		Probablity of Visitation	Avoided number of people potentially exposed		Cumultaive relative risk	Avoided number of potential G1 illness		Value of an avoided G1 illness	Avoided number of potential gl illness	
		Min	Max		Min	Max		Min	Max		Min	Max
13	2	1,024	4,099	0.50	13,312	53,287	0.05	666	2,664	$410	$272,896	$1,092,384

Since the values are based on the relative probabilities of either decision pathway, they can be aggregated. The annual VOI, therefore, is $565 thousand to $2.3 million for the state of Kansas alone.

DISCUSSION

The major finding of this case study is that there is a societal impact from cyanoHABs in the state of Kansas, for which additional - including earlier - information on whether a cyanoHAB is producing cyanotoxins would likely lead to avoided effects (such as human health and recreation), and that cyanoHAB research and monitoring is currently contributing and could potentially contribute additional societal values. The findings indicate a value of $565 thousand to $2.3 million in annual benefits for Kansas under the suite of scenario assumptions. This represents the value of two additional days provided by the early warning system. Another potentially large improvement in information that could be realized from the early warning system or cyanotoxin research is the set of conditions that result in a toxic event. Current advisories and closures rely on cyanobacteria cell counts; KDHE found that 60% of the time that cell counts warranted advisories, samples were negative for microcystin (it should be noted that microcystin is the only cyanotoxin tested for and other, unmeasured cyanotoxins also may be present). Better prediction of whether a bloom is toxic could potentially prevent closures for entire events. Using 2018 data and an average duration of events of 9 weeks, this could increase benefits by $26 to $104 million in avoided recreational losses.

This case study relied on a number of assumptions, data on incidence of cyanoHABs for a single year in a single state, and benefits transfer to estimate the VOI. To the extent that the benefit transfer values do not represent actual preferences in the state of Kansas (such as the estimate for the value of a freshwater beach recreational day or the value of avoiding a gastrointestinal illness) the results will under or over represent the actual value. The assumptions, including the expectation that an early warning system will provide two additional days of information may bias the results. To the extent that an early warning system provides more or less information, the benefits of the information will similarly be greater or fewer than we estimate in this case study. Additionally, the only benefits estimated are those associated with reduced gastrointestinal illness and avoided foregone freshwater beach recreation; there may be additional health effects both acute and long-term as well as other effects related to cyanoHABs that have not been estimated. These results can therefore be considered as the lower bound of the VOI. Finally, the analysis is constrained to the state of Kansas. Simple extrapolation is not possible due to the current analysis incorporating place-specific preferences and costs, including willingness to pay for freshwater beach going and cost of illness for gastrointestinal illness. Recreation and exposure information is also Kansas specific. This analysis does provide a framework that could be parameterized with place-specific data for other locations. This study indicates that the value of research and information on cyanoHABs for the Nation is potentially much larger than our results for Kansas alone.

CONCLUSION

The purpose of this case study was to consider the magnitude of economic impacts associated with cyanoHABs in the United States, to demonstrate the approach of using decision trees to better understand the use and users of a cyanoHAB early warning system which incorporates USGS cyanoHAB research, and to estimate the VOI for a cyanoHAB early warning system in a pilot-scale study. The results indicate that an early warning system based on cyanobacterial cell counts and/or potential toxicity would provide positive economic benefits for the state of Kansas in the use of managing freshwater lakes during cyanoHAB events. It is also likely that this benefit can be extended to other states and in other applications. As toxic cyanoHABs continue to emerge as a major water quality issue in the United States, increased cyanoHAB understanding and an early warning system can provide managers with earlier information to avoid impacts leading to societal value; in addition, advancing the understanding of the causes of

why and when cyanoHABs become toxic can potentially help to avoid or mitigate cyanotoxin events. Ongoing economic research coupled with the science supports understanding the users and uses of the information which can help fine tune the research for the most impact, demonstrate a return on research investment, and illustrate the societal benefits of cyanoHAB science.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

EP provided economic expertise, study design, and developed the initial draft. KL provided geochemistry expertise, input on study design, and authored sections of the draft.

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