Watershed integrity and associations with gastrointestinal illness in the United States

Jyotsna S. Jagai, Alison K. Krajewski, Monica P. Jimenez, Mark S. Murphy, Scott G. Leibowitz and Danelle T. Lobdell

ABSTRACT

Gastrointestinal (GI) illnesses are associated with various environmental factors, such as water quality, stormwater runoff, agricultural runoff, sewer overflows, and wastewater treatment plant effluents. However, rather than assessing an individual factor alone, two indices incorporating a combination of ecological and environmental stressors were created to represent (1) overall watershed integrity, Index of Watershed Integrity (IWI) and (2) catchment integrity, Index of Catchment Integrity (ICI). These indices could provide a more comprehensive understanding of how watershed/catchment integrity potentially impact the rates of GI illness, compared to assessing an individual stressor alone. We utilized the IWI and ICI, as well as agricultural and urban land uses, to assess associations at the county level with the rates of GI illness in a population of adults over 65 years of age. Our findings demonstrated that both watershed and catchment integrity are associated with reduced hospitalizations for any GI outcomes, though association varied by urbanicity.

We believe that improved versions of the IWI and ICI may potentially be useful indicators for public health analyses in other circumstances, particularly when considering rural areas or to capture the complex stressors impacting the ecological health of a watershed.

Key words | gastrointestinal illness, water quality, watershed integrity

INTRODUCTION

In the United States, it is estimated that approximately 477,000 annual emergency room visits are documented for 13 diseases, the majority of which were gastrointestinal (GI) infections, caused by pathogens that can be transmitted by water (CDC 2017). Most waterborne pathogens that cause GI illness are due to exposure to human and animal feces, which are either deposited directly into water bodies or transported to water bodies by surface or subsurface water flow. In urban areas, pathogens can be transported by stormwater runoff, sewer overflows, and wastewater treatment
plant effluents. Infection in humans can be caused by direct contact with contaminated waters or food products (e.g., fish) or by human-to-human transmission. Increases in GI illnesses are also associated with various environmental factors, such as water quality, and meteorological factors, such as precipitation and temperature (Ballester & Sunyer 2000; Hsieh et al. 2015; Bylund et al. 2017; De Roos et al. 2017). For this reason, GI illnesses may be associated with watershed integrity, which incorporates many environmental factors that are related to water quality (Kuhn et al. 2018; Thornbrugh et al. 2018). Watershed integrity is the capacity of a watershed to support and maintain the full range of ecological processes and functions essential to the sustainability of biodiversity and of the watershed resources and services provided to society (Flotemersch et al. 2016). As such, a lack of watershed integrity could result in an absence of resources and ecosystem services and may be a useful tool to predict GI illness in a community.

Watershed integrity cannot be measured directly, so an operational definition of watershed integrity based on a risk-based approach has been developed (Flotemersch et al. 2016). Watershed integrity is defined as the ability of a watershed to provide six key functions: hydrologic regulation, regulation of water chemistry, sediment regulation, hydrologic connectivity, temperature regulation, and habitat provision (Flotemersch et al. 2016). Using these six key functions, an Index of Watershed Integrity (IWI) was developed that defines integrity based on the presence of stressors that are known to affect these key functions. For example, the presence and volumes of reservoirs and percent impervious surfaces are considered as stressors of hydrologic regulation. Additionally, alteration to and spatial arrangement of riparian vegetation and the presence and density of mines, logging, and roads are stressors of sediment regulation.

More recently, Thornbrugh et al. (2018) used the Flotemersch et al. (2016) concept to map the IWI across the conterminous United States (all states and DC, excluding Alaska and Hawaii). In addition, a related Index of Catchment Integrity (ICI) was developed. A catchment is defined as the local drainage that flows directly into an individual stream segment, excluding upstream contributions, while a watershed consists of all the area contributing flow to a stream segment, including local and upstream catchments (Thornbrugh et al. 2018). The IWI and ICI were mapped for the 2.6 million watersheds and catchments (average size 3 km²) in the conterminous United States using stressor data from the EPA’s StreamCat Dataset (Hill et al. 2016). StreamCat contains over 500 landscape variables at catchment and watershed scales that were derived from nationally available datasets. Differences in relative values between the IWI and ICI could provide information on whether water quality problems arise from local (catchment) or upstream (watershed) sources (Aho et al. Submitted; Hill et al. 2017).

Since the IWI and ICI capture a number of factors that may be associated with human health, particularly GI illness, we consider whether the rates of GI illness in the United States are associated with either IWI or ICI and which of these indices is a stronger predictor of GI illness rates. Additionally, we consider if the IWI and ICI provide stronger associations than considering the percent of land coverage for agriculture or urban alone. These two land uses are important components of the IWI and ICI, and any relationship with GI illness could be due to agricultural or urban land use alone. A stronger relationship with the IWI or ICI would indicate that the other stressors included in these indices are valuable for understanding GI illness distributions. We hypothesize that counties with higher values of IWI and ICI will have lower rates of GI illness among adults over 65 years of age, a population that is vulnerable to GI infection; and that IWI and ICI will demonstrate stronger associations with GI illness rates than either agricultural or urban land coverage alone.

METHODS

We utilized the developed watershed (IWI) and catchment (ICI) integrity indices to assess associations at the county level with the rates of GI illness in a population of adults over 65 years of age. Additionally, we considered the percentage of agricultural and urban land uses as exposure variables to assess the utility of the IWI and ICI.

Outcome data

The health outcome data were abstracted from hospitalization records from the Center for Medicare and Medicaid...
Services (CMS) (CMS 2018). The Medicare program is a U.S. federal insurance program primarily for those over 65 years of age. It is estimated that about 95% of the U.S. population over 65 years of age are enrolled in this program. Hospitalization records for adults aged 65 years or over were obtained from Medicare data for 2006 through 2010 for the conterminous United States. Each hospitalization record contains patient information on age at admission, sex, race, date of admission and date of discharge, state, county Federal Information Processing Standards (FIPS) code, and primary diagnosis code. The study and use of hospitalization data were approved by the EPA’s National Health and Environmental Effects Research Laboratory’s Human Research Protocol Office. Specifically, we used the Medicare dataset which is claims data for those in the Medicare program.

Hospitalization records were extracted based on the International Classification of Diseases, Ninth Revision codes (ICD9). Three different GI variables were created based on the primary diagnosis of the following ICD9 codes: GI infections (GI only) without Clostridium difficile (ICD 9 codes 001-009, excluding 008.45), GI symptoms (GS only) (ICD 9 codes 558.9 and 787), and any GI outcomes without Clostridium difficile (ICD 9 codes 558.9, and 787 and 001-009, excluding 008.45), which combined the ICD 9 codes from GI only and GS only into one category. Clostridium difficile (ICD 9 code 008.45) was excluded because it is primarily a nosocomial, hospital-acquired, infection (Mcfee 2009a, 2009b). Between 2006 and 2010, the number of people hospitalized for GI outcomes was as follows: 510,799 (any GI outcome), 142,958 (GI only), and 379,664 (GS only). The hospitalizations for an individual during this time period are not mutually exclusive, meaning that a person could have a primary diagnosis of GS during one hospitalization and have a GI during a different hospitalization, and/or have multiple hospitalizations for GI outcomes during the time period. Rates of the number of people hospitalized by GI outcome were calculated by county. The total number of people who were hospitalized by GI outcome in a county was divided by the total number of Medicare participants in the county; this was then multiplied by 100,000 to convert to a GI rate per 100,000 Medicare participants. The total number of people in the Medicare dataset was 43,134,091. County FIPS codes were used to link the CMS data to the exposure data.

**Exposure data and spatial analysis**

The IWI and ICI are indices created to represent the overall watershed and/or catchment quality based on a set of predefined stressors to six key watershed functions (hydrologic regulation, regulation of water chemistry, sediment regulation, hydrologic connectivity, temperature regulation, and habitat provision). This combination of stressors could provide a more comprehensive understanding of the ecological and environmental factors that potentially impact the rates of GI illness than individual stressors alone.

The IWI and ICI values are based on landscape physical features, i.e., watersheds and catchments, respectively; details on the calculation of these two indices are given in Thornbrugh et al. (2018). In contrast, the GI illness data are available by political units, e.g., counties. To compare these two types of data, they first must be converted to a common unit. To do this, we first downloaded IWI and ICI (v1) data from the StreamCat Dataset (Hill et al. 2016). IWI and ICI values were multiplied by 100 to convert from a 0–1 to 0–100 range, for compatibility with the agricultural and urban land uses. We then converted the spatially discrete catchment maps to a continuous, 30 m raster for the conterminous United States using a simple inverse distance weighting (Lu & Wong 2008; Van Sickle & Johnson 2008) approach:

\[
I_{r,\text{IDW}} = \sum_c \frac{I_c}{d_r,c} \quad \text{for all catchments } c \text{ having } d_r,c \leq 200 \text{ km}
\]

(1)

where \(I_{r,\text{IDW}}\) is the inverse distance-weighted integrity of the raster cell \(r\), \(I_c\) is the watershed or catchment integrity associated with catchment \(c\), and \(d_{r,c}\) is the distance (km) between raster cell \(r\) and the centroid of catchment \(c\).

We associate both the watershed and catchment integrity values with the catchment, rather than associating the IWI with the entire watershed; i.e., the catchment centroid is used in determining the distance. The IWI value is associated with the catchment for two reasons. First, catchments of consecutive stream segments are nested and overlap.
That means that it is not possible to map the IWI values for all watersheds simultaneously. This is because the IWI value for one watershed would obscure the IWI values for all upstream watersheds. Second, while watershed integrity for stream segment \( c \) is calculated from stressors occurring in its local and upstream catchments, it is only stream segment \( c \) that could be impacted by those accumulated stressors: segments upstream from segment \( c \) would not be affected by stressors in catchment \( c \), and downstream segments would also respond to downstream catchments. Thus, we associate the watershed integrity value with the local catchment surrounding stream segment \( c \) (see Thornbrugh et al. 2018) for more discussion on mapping alternatives.

Since differences in the population can affect trends in GI illness, we also needed to population weight the final integrity values. Because population can vary substantially across a county, we used census tract population data to increase the spatial resolution. First, we used the raster from Equation (1) to calculate the integrity values for each census tract in the conterminous United States:

\[
I_{t-IDW} = \frac{\sum_{r} I_{t-IDW}}{\text{count}(r \in t)} \quad \text{for all raster cells } r \text{ in tract } t
\]

where \( I_{t-IDW} \) is the IDW integrity of census tract \( t \) and count \( (r \in t) \) is the count of raster cells \( r \) in tract \( t \). This value, along with population and area information, was then used to calculate an IDW and population-weighted county level integrity:

\[
I_{t-\text{IDW,POP}} = \frac{\sum_{t} I_{t-IDW} \times p_{t} \times a_{ctnty/t} \times a_{t}}{p_{ctnty} \times a_{t}}
\]

for all tracts \( t \) in county \( ctnty \)

where \( I_{t-\text{IDW,POP}} \) is the inverse distance and population-weighted integrity for county \( ctnty \), \( p_{t} \) and \( p_{ctnty} \) are the TIGER2010 (US Census Bureau 2018) census data populations of tract \( t \) and county \( ctnty \), respectively, \( a_{ctnty/t} \) is the joint area (intersection) of county \( ctnty \) and tract \( t \), and \( a_{t} \) is the area of tract \( t \) (areas in km²).

For comparisons of IWI and ICI performance with land use, we used the ArcGIS (v10.4.1) Tabulate Area tool (ESRI, Redlands, CA, 2016) to calculate percent agricultural and urban land use by county based on the 2006 National Land Cover Dataset (USGS 2018). We defined agriculture based on NLCD classes 81 (pasture/hay) and 82 (cultivated crops) and urban using classes 21 (developed, open space), 22 (developed, low intensity), 23 (developed, medium intensity), and 24 (developed, high intensity).

**Statistical analysis**

Generalized linear models were used to assess associations between the four exposure variables (IWI, ICI, agriculture, and urban) and three hospitalization rate outcomes (any GI outcome, GI only, or GS only). We considered two covariates, population density and percent of population over 65, which were included in the regression models. Four generalized linear models were fit for each GI outcome hospitalization rate by each exposure: (1) crude model, (2) adjusting for population density, (3) adjusting for percent of the population over 65 years of age, and (4) adjusting for both population density and percent of the population over 65 years of age. If any of the county level GI outcome hospitalization rates, any GI outcome, GI only, or GS only were equal to zero, they were excluded from the analysis, which accounted for 12 (0.39%), 60 (1.93%), and 17 (0.55%) counties in our study, respectively. Additionally, analyses were stratified based on rural/urban status to account for differences in drivers of water quality and land use across the country. We utilized four categories of rural–urban classification that combine nine Rural–Urban Continuum Codes (RUCCs) developed by the U.S. Department of Agriculture for U.S. counties (USDA 2016). The four categories are RUCC1 – metropolitan urbanized, RUCC2 – non-metro urbanized, RUCC3 – less urbanized, and RUCC4 – thinly populated. These categories have been previously used in public health analyses (Messer et al. 2010; Langlois et al. 2010; Jagai et al. 2017). Models were run in SAS v9.4 (SAS Institute, Cary, NC, 2018) using a GENMOD procedure.

We evaluated the strength of association of the four exposure variables considered with the rates of GI illness using the resulting effect estimates from these models. A positive effect estimate indicates that the exposure variable is associated with an increase in hospitalization rates of GI outcomes (i.e., higher rate of hospitalizations), while a
negative estimate indicates a decrease in hospitalization rates of outcomes.

RESULTS

The rate of hospitalizations for the three outcomes considered (any GI outcome, GI only, and GS only) varied significantly by county (Table 1, Figure 1) for the study period, 2006–2010. The rate of the number of people hospitalized for any GI outcome ranged from 0 to 8,084.4 per 100,000 (mean 1,507.6 ± 812.2) across counties. The rate of the number of people hospitalized for GI only across counties ranged from 0 to 3,653.6 per 100,000 people (mean 361.1 ± 221.2). The rate of the number of people hospitalized for GS only ranged from 0 to 6,789.0 per 100,000 people (mean 1,180.8 ± 738.4) across counties.

The exposure variables of interest (IWI, ICI, agriculture, and urban) also demonstrated variation across counties (Table 2, Figure 2). The percent IWI ranged from 13.7 to 90.9 across counties, with a mean 45.9 ± 18.8. For percent ICI, the range across counties was 14.8–90.2, with a mean of 47.4 ± 17.1. For the percent of agricultural land use across counties, the range was 0–93.6 with a mean of 31.8 ± 26.3. The range for percent urban land use across counties was 0.2–94.0 with a mean 9.0 ± 12.3.

On average, hospitalization rates for all three outcomes increased with rurality, with the highest rates seen in RUCC4, the thinly populated stratum (Supplemental Table 1). The most rural counties also demonstrated the most variability across counties with the largest range and standard deviation of hospitalization rates. Similarly, the highest percentages of IWI and ICI were seen with increasing rurality, RUCC3 and RUCC4 (Supplemental Table 2).

On average, the percent of land in agriculture was similar in RUCC2, RUCC3, and RUCC4. The four models considered, (1) crude, (2) adjusted for population density, (3) adjusted for population over 65, and (4) adjusted for both, demonstrated similar trends for all analyses with slight variations in estimates. Therefore, we present results for the fully adjusted models, controlling for population density and percent of population over 65 years of age (results for other models are in the supplemental materials, Supplemental Figures 1–3). Regression analyses demonstrated a consistent inverse association between IWI and ICI and rates of hospitalization for all GI outcomes (Figure 3). Therefore, for all counties, as watershed or catchment integrity increased, the rates of hospitalizations for GI illness decreased. For every one-percent increase in IWI, the number of people hospitalized for any GI illness decreased by 5.0 per 100,000 Medicare participants (95% CI: −6.5, −3.5). Increase in IWI was also associated with decreased rates of hospitalizations for GI and GS alone. ICI was also associated with a decrease in rates of hospitalizations for all GI outcomes, though the magnitude of association was not as strong. For every one-percent increase in ICI, the number of people hospitalized for any GI illness decreased by 3.1 per 100,000 Medicare participants (95% CI: −4.8, −1.5). Additionally, IWI and ICI were both more strongly associated with rates of GS hospitalizations only than with rates of GI hospitalizations only. An increase in the percent of land in agriculture was associated with an increase in the rates of all three GI outcomes considered. For a one-percent increase agricultural land, the hospitalization rate for any GI increased by 4.9 per 100,000 Medicare participants (95% CI: 3.9, 6.0). Percent land in agriculture was more strongly associated with rates of GS hospitalizations only (4.1, 95% CI: 3.2, 5.1) than with rates of GI hospitalizations only (0.7, 95% CI: 0.4, 1.0).

Table 1 | Descriptive statistics for the rates of the number of people hospitalized for GI outcomes per 10,000 Medicare participants by hospitalization type, 2006–2010

<table>
<thead>
<tr>
<th>Hospitalization typea</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of hospitalizations of people for any GI outcomes, per 100,000</td>
<td>3,108</td>
<td>1,507.62</td>
<td>812.19</td>
<td>1,316.99</td>
<td>0</td>
<td>8,084.36</td>
</tr>
<tr>
<td>Rate of hospitalizations of people for GI outcomes only, per 100,000</td>
<td>3,108</td>
<td>361.09</td>
<td>221.22</td>
<td>325.26</td>
<td>0</td>
<td>3,653.59</td>
</tr>
<tr>
<td>Rate of hospitalizations of people for GS outcomes only, per 100,000</td>
<td>3,108</td>
<td>1,180.77</td>
<td>738.41</td>
<td>990.06</td>
<td>0</td>
<td>6,788.99</td>
</tr>
</tbody>
</table>

aHospitalization rate types are not mutually exclusive.
An increase in the percent of urban land was associated with a decrease in rates of hospitalizations for all three GI outcomes. For a one-percent increase in urban land, the hospitalization rate for any GI decreased by 7.1 per 100,000 Medicare participants (95% CI: −9.8, −4.4).

Again, stronger associations were seen with rates of GS hospitalizations only (−7.6, 95% CI: −10.0, −5.1) than with rates of GI hospitalizations only (−0.1, 95% CI: −0.8, 0.7).

When considering associations by rural/urban stratification, IWI and ICI demonstrated similar trends across all

Figure 1 | Rates of the number of people aged 65 and older hospitalized by any GI outcome (a), GI infections only (b), and GI symptoms (c) per 100,000 Medicare participants, 2006–2010.
stratification categories (Figure 3). Across all RUCC, an increase in the percent watershed or catchment integrity was associated with decreased rates of hospitalizations, with the exception of GI hospitalization rate only for RUCC1, where ICI was associated with a slight increase. In contrast, increases in the percent of agriculture or urban land use were generally associated with increased hospitalization rates. For any GI and GS only outcomes, the strongest associations for all four exposures were in the thinly populated strata (RUCC4). For the GI only outcome, however, rural/urban stratification had little effect.

In RUCC1, IWI demonstrated the strongest magnitude of effect for all three GI outcomes. The results for the percentage of land in agriculture or urban varied by RUCC. The thinly populated stratum, RUCC4, demonstrated the strongest associations with both IWI (−12.4, 95% CI: −16.7, −8.1) and ICI (−11.8, 95% CI: −16.6, −8.1). Across all RUCC strata, as the percentage of agricultural land increased, the rate of hospitalizations for GI illness increased. The strongest association was seen in the thinly populated stratum, RUCC4,

Table 2  Descriptive statistics by exposure of interest, 2006–2010  

<table>
<thead>
<tr>
<th>Exposure of interest (%)</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>IWI</td>
<td>3,108</td>
<td>45.91</td>
<td>18.83</td>
<td>45.18</td>
<td>13.67</td>
<td>90.88</td>
</tr>
<tr>
<td>ICI</td>
<td>3,108</td>
<td>47.36</td>
<td>17.14</td>
<td>46.49</td>
<td>14.83</td>
<td>90.24</td>
</tr>
<tr>
<td>Agriculture</td>
<td>3,108</td>
<td>31.84</td>
<td>26.30</td>
<td>24.18</td>
<td>0</td>
<td>93.58</td>
</tr>
<tr>
<td>Urban</td>
<td>3,108</td>
<td>9.01</td>
<td>12.33</td>
<td>5.81</td>
<td>0.16</td>
<td>94.05</td>
</tr>
</tbody>
</table>

Figure 2  Exposure: IWI (a), ICI (b), agricultural land use (c), and urban land use (d), by quintiles.
which demonstrated a one-percent increase in land for agriculture was associated with 6.84 hospitalizations per 100,000 Medicare participants (95% CI: 3.8, 9.8). The percent of urban land demonstrated positive associations for all strata except in metropolitan urban counties, RUCC1, which demonstrated a negative association with any GI hospitalization rates (−0.5, 95% CI: −2.1, 1.2) and GS hospitalization rates only (−1.0, 95% CI: −2.5, 0.5) and positive associations with GI hospitalization rates only (0.5, −0.0, 1.0). Results for the other models by RUCC stratification are in the supplemental materials (Supplemental Figures 1–3).

**DISCUSSION**

Our findings demonstrated that both watershed and catchment integrity are associated with reduced rates of hospitalizations for any GI outcomes, though the magnitude of association varied by urbanicity. These indices, which are measures of the capacity of a watershed to support ecological processes, have been correlated with water quality (Kuhn et al. 2018) and therefore we hypothesized that they should be associated with GI outcomes. Overall, we found that as watershed integrity increased, the rate of GI illness decreased. These findings were expected as previous...
studies have demonstrated associations between decreased water quality and GI infections (MacDougall et al. 2008; Hsieh et al. 2015; Bylund et al. 2017; De Roos et al. 2017). However, our findings are not directly comparable to previous studies, as IWI and ICI are not measures of water quality per se, but rather are broader measures of the ecological health of a watershed and therefore correlated with water quality. We originally hypothesized that IWI and ICI would have negative relationships with GI rates, and confirmed that this was the case; the magnitude of association with GI illness was stronger with IWI compared to ICI. This suggests that GI illnesses may be dependent on upstream characteristics, and not just the characteristics of the local catchment. Alternatively, this finding could be because the spatial scale of the watershed, rather than the catchment, may be more similar to the county, which is the level of aggregation of the hospitalization data.

Additionally, we found that land use characteristics, the percent of urban land and percent of agricultural land were also associated with any GI outcomes and varied by urbanicity. The percentage of land in a county used for agriculture is often used as a proxy for farming and intensive land use which can decrease local water quality and therefore impact health, such as GI, outcomes (Bylund et al. 2017). The percent of urbanized land is often used as a proxy for access to improved water sources, healthcare, and therefore associated with decreased rates of GI outcomes (Bylund et al. 2017). However, we found that this was only true for metropolitan urban areas (RUCC1) and was not the case for urban areas in RUCC2-4.

We found that the associations for all exposures considered varied by urbanicity. Associations with IWI and ICI were the weakest in the metropolitan urbanized counties and stronger in the other three strata, with the strongest associations in the thinly populated strata. Similarly, the percent of urban land use demonstrated stronger associations in the less urban stratum with the strongest associations in the thinly populated stratum. Whereas the percent of land in agriculture had similar associations in all strata with slightly stronger associations with increasing rurality. The reduced strength of associations in the most urbanized strata may be due to the limited variability in the exposures, IWI, ICI, and percent urban in these strata.

While the trends remained the same, we also saw differences in the strength of association between the rates of GI hospitalizations and rates of GS hospitalizations outcomes, with rates of GS hospitalizations demonstrating stronger associations. These differences are likely due to the higher rates and more hospitalizations seen for GS only. GI symptoms are diagnosed and recorded more often in hospitalization claims’ data since they do not require laboratory confirmation of infection and pathogen. GI infections are underreported in hospitalization data due to the burden of laboratory confirmation (MacDougall et al. 2008; Hsieh et al. 2015). Additionally, we considered only primary diagnosis, rather than all diagnoses, in this analysis and therefore it is likely that hospitalizations for both GI symptoms and infections are underreported.

We hypothesized that IWI and ICI would demonstrate stronger associations with GI rates than percent agricultural and urban land use, which are components of the integrity indexes. Instead, our study demonstrated that the strongest relationships with rates of GI hospitalizations were found with percent urban, and that results for IWI and ICI had similar associations with percent agriculture. However, we believe that the IWI and ICI could still potentially be useful indicators for public health analyses. First, we note that IWI demonstrated strong associations in the metropolitan urban areas and so could be useful for smaller scale studies in these areas. Second, the Thornbrugh et al. (2018) maps assume negative linear relationships between stressors and functions, as well as the equal weighting of stressors. More recently, Johnson et al. (2019) have shown how to revise the indices by fitting stressor and function data using random forests. Revised IWI and ICI maps could perform better than the version used here. Third, in our study, we are using Medicare data and considering a population of elderly who are less likely to have direct contact with water sources. However, the IWI and ICI may be more strongly associated with GI outcomes in a younger population who are likely to interact directly with water sources. Finally, IWI and ICI are broad indicators of the ecological health of the watershed and may be useful when considering other health outcomes. In particular, the IWI and ICI may be more useful indicators for public health analyses in rural areas for diseases not associated
with urbanization, since this is where they demonstrated the strongest associations in this analysis.

CONCLUSION

The IWI and the ICI were assessed as exposures for rates of hospitalizations for GI illness. While our study demonstrated similar associations with percent of agriculture, we believe that improved versions of the IWI and ICI may potentially be useful indicators for public health analyses in other circumstances, particularly when considering rural areas or to capture the complex stressors impacting the ecological health of a watershed.

ACKNOWLEDGEMENTS

Thanks to Marc Weber for providing GIS datasets and analysis and to Tony Olsen, Jay Ver Hoef, and Eric Fox for suggestions on how to convert IWI and ICI data from catchments to counties. Thanks to Sarah Hoffman, Christine Gray, and Stephanie DeFlorio-Barker for providing assistance with data cleaning and aggregation for the CMS data. The views expressed in this manuscript are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at http://dx.doi.org/10.2166/wh.2019.060.


