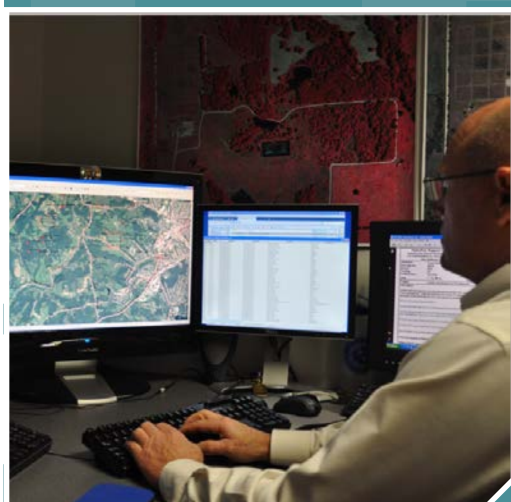
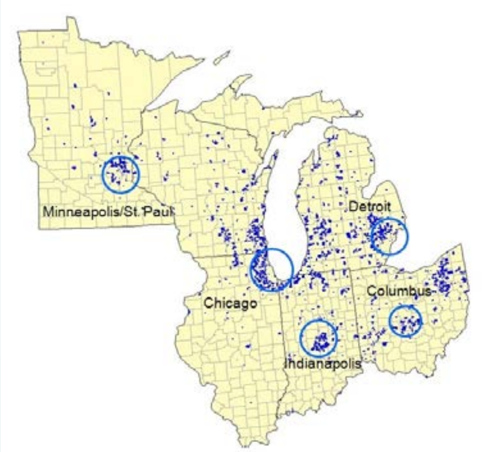
EPA/600/R-11/108 | December 2011 | www.epa.gov/ada

EPA
United States
Environmental Protection
Agency

GIS Analysis to Assess where Shallow Ground Water Supplies in the United States are Vulnerable to Contamination by Releases of Motor Fuel from Underground Storage Tanks





Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

GIS Analysis to Assess where Shallow Ground Water Supplies in the United States are Vulnerable to Contamination by Releases of Motor Fuel from Underground Storage Tanks

Rob Earle
Shaw Environmental, Inc.

John T. Wilson
U.S. EPA/ORD/NRMRL Ground Water and Ecosystems Restoration Division

Fran Kremer
U.S. EPA ORD/NRMRL

Jim Weaver
U.S. EPA/ORD/NRMRL Ground Water and Ecosystems Restoration Division

David Burden, Project Officer
U.S. EPA/ORD/NRMRL Ground Water and Ecosystems Restoration Division

Office of Research and Development
National Risk Management Research Laboratory, Ada, Oklahoma 74820

Notice

The U.S. Environmental Protection Agency through its Office of Research and Development funded and managed the research described here under contract to Shaw Environmental Inc. (EP-C-08-034, work assignment CSMoS 2-04). It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Spills of motor fuel from underground storage tanks are an important source of contamination to ground water. This report provides a simple approach to identify those geographical regions of the USA where shallow ground water that is used as a source of drinking water is more vulnerable to contamination from fuel spills from underground storage tanks. This screening approach identifies those geographical areas where efforts to prevent spills or to manage spills from underground storage tanks will have the greatest benefit to protect shallow ground water as a source of drinking water.

David G. Jewett, Acting Director
Ground Water and Ecosystems Restoration Division
National Risk Management Research Laboratory

Contents

Figures

Tables

Acknowledgements

Joel Hennessy (U.S. EPA Region 3) provided valuable guidance to this project.

Peer reviews were provided by Bob Pallarino (U.S. EPA Region 9), Joel Hennessy (U.S. EPA Region 3), Jack Hwang (U.S. EPA Region 3), Frederick McGarry (New Hampshire Department of Environmental Services), Mark Barolo (U.S. EPA Office of Underground Storage Tanks), Hal White (U.S. EPA Office of Underground Storage Tanks), Stephen Reuter (New Mexico Environmental Dept), Carol Eighmey (Missouri Petroleum Storage Tank Insurance Fund), John Menatti (Utah Department of Environmental Quality) and Jeff Kuhn (Montana Department of Environmental Quality).

Figure 1 from Ayotte et al., 2008 as included in Figure 9 is reprinted with permission from Ayotte, J. D., D. M. Argue, F. J. McGarry, J. R. Degnan, L. Hayes, S. M, Flanagan and D. R. Helsel. Methyl *tert*-Butyl Ether (MTBE) in public and private wells in New Hampshire: occurrence, factors, and possible implications. *Environmental Science & Technology* 42, 677–684. (2008), copyright 2008, American Chemical Society.

Abstract

Geographic Information Systems (GIS) were used to assess the vulnerability of ground water supplies to contamination. The analysis was conducted for the 48 contiguous United States, and then again for groups of states corresponding to the EPA Regions. The long form of the 1990 census asked the respondents where they got the water for their home. The choices were: (1) a public system such as a city water department or private company; (2) an individual drilled well; (3) an individual dug well; or (4) some other source such as a spring, creek, river, cistern, etc. The reported estimates for the numbers of drilled wells, dug wells, and other supplies of water were summed to obtain an estimate of the number of households in each census block group that obtained water from a private source. The 1990 census also reported the surface area [square miles] of each census block group. A data file was purchased from ESRI Business Solutions that contained the latitude and longitude of active retail gasoline service stations in the United States. Using Geographical Information System tools (GIS tools) and geo-referenced GIS coverage files on each census block group, the latitude and longitude of each active service station was used to assign the service station to a census block group. Then the number of service stations in each census block group was summed. A simple probability analysis was performed based on the distribution of service stations and the distribution of the households that obtained water from a private supply. Three separate indices were calculated. Each index was calculated for those census block groups that had at least one service station and at least one household that obtained water from a private source.

Vulnerability Index 1 is simply the density of service stations in each census block group. It is calculated as the number of service stations in each census block group divided by the area of each census block in square miles. It provides an estimate of the possibility that the water supplied to a household from a private source will be impacted by a service station. Vulnerability Index 1 describes the consumer's risk of having his water supply impacted.

Vulnerability Index 2 is the density of households in each census block group that obtain water from a private source. It is calculated as the number of households in each census block group that obtain water from a private source divided by the surface area of the block group in square miles. It provides an estimate of the possibility that a release from a particular service station will impact the water supplied to a household that obtains water from a private source. Vulnerability Index 2 describes the risk to the service station owner that a release from his station will impact someone's private water supply.

To describe the risk to the entire community that obtains ground water from shallow sources, the index that describes the possibility that a single household might be impacted was multiplied by the number of households that are at risk. Vulnerability Index 3 was calculated by multiplying Vulnerability Index 1 for each block group by the number of households in each block group that obtain water from a private source. Vulnerability

Index 3 describes the resource manager’s risk that a release from a gasoline service station in their geographic area will impact the private water supply of a household in their geographic area.

The report provides maps showing the distribution of census block groups that fell into the highest 30%, the highest 10%, the highest 3% and the highest 1% of census block groups for each Vulnerability Index.

1.0 Introduction

Petroleum gasoline contains, among many other components, benzene, toluene, ethylbenzene, and xylenes (BTEX). Gasoline may also contain ethanol, methyl tertiary butyl ether (MTBE), tertiary butyl alcohol (TBA), or other alcohols and ethers used as fuel oxygenates. Leaded gasoline contains an organolead compound such as tetraethyl lead (TEL) and the lead scavengers ethylene dibromide (EDB) and 1,2-dichloroethane (DCA). If gasoline is released from an underground storage tank (UST) at a gasoline service station, these compounds can contaminate ground water. The US Geological Survey (USGS) in a nationwide study found that these gasoline compounds are the third most commonly detected class of organic contaminants in ground water (Zogorski et al., 2006).

There are several factors that may contribute to potential impacts of releases from underground storage tanks on water supplies. One factor deals with the composition of the fuels. The requirements of the Renewable Fuel Standard (RFS) established by the Energy Policy Act of 2005 and amended by the Energy Independence and Security Act of 2007 have increased the use of biofuels in the nation's fuel supply. This change in the fuel supply can alter the spread of gasoline hydrocarbons in ground water resulting from underground storage tank releases.

Field demonstrations supported in part by the U.S. EPA's Office of Research and Development (Mackay et al., 2006) and others (Corseuil et al., 2011) have shown that ethanol can inhibit the natural anaerobic biodegradation of BTEX compounds, causing dissolved plumes of BTEX in ground water to be larger than they otherwise would be. When a readily fermentable biofuel, such as ethanol, is included in the fuel spill, the biofuel will be degraded to acetate and molecular hydrogen. The acetate and hydrogen will accumulate in ground water until they make the anaerobic biodegradation of benzene and other BTEX compounds thermodynamically unfeasible (Corseuil et al., 2011). As long as the biofuel persists in ground water, degradation of the biofuel to acetate and hydrogen will preclude natural anaerobic biodegradation of benzene and other BTEX compounds. Anaerobic biodegradation of benzene cannot begin until the biofuel, and its transformation products, have been degraded (Corseuil, et al, 2011). This means that if ethanol is present in motor gasoline, there is a greater chance that BTEX from a spill of gasoline will impact a water supply well. Given this projected impact on BTEX contamination, it is reasonable to assume that when a UST release occurs, the likelihood of the plume reaching a water supply well is greater when the release is from a UST storing ethanol-blended fuel. The increased use of biofuels makes it even more important to understand the potential interaction between releases of motor fuel from underground storage tanks and the impacts to ground water supply.

There are spatial and temporal interactions that operate at a regional scale that may affect the future supply of ground water. As the population grows, the demand for ground water will increase. This is particularly true in suburban landscapes that are not served by a municipal or regional water supply. An increase in the number of homes that are served by private wells will increase the potential for an impact. If climate change brings drought that reduces precipitation and subsequent recharge of ground water supplies, the potential for impacts will increase. If pumping and stream discharge exceed the recharge to the aquifer, the water table in an aquifer will drop.   As the water table drops, the zone of capture of a water supply well must expand to be able to supply the same amount of water.   As the zone of capture expands, the chance of pulling in contaminated ground water increases. Any useful understanding of these potential interactions at some time in the future must build on an understanding of the current vulnerability of ground water to contamination.

There are many local conditions that may contribute to potential impacts of releases from underground storage tanks on water supplies: the locations of the underground storage tanks (USTs); the types of fuels stored in USTs; the quality of installation; the volume of fuel flowing through the UST system and the number of dispensers; the operating and maintenance practices of the UST owner/operator; the local subsurface soil, geology and hydrogeology; the distance to and density of nearby water supply wells; and the depth and construction features of the wells. This information is collected and organized by the individual state agencies that implement the underground storage tanks program. Each state agency organizes the data in the manner that best suits its purposes. Unfortunately, these data are not compiled in a consistent format that would allow comparisons from one state to another. At the present time, any analysis of these local conditions must be carried out by the individual states or local governments. However, data are available at a national scale for three important parameters – the density of households that use shallow ground water for drinking water, the density of UST systems, and the co-location of gasoline service stations and households that use shallow ground water for drinking water.

Geographic Information Systems (GIS) were used to assess the vulnerability of ground water supplies to contamination based on these three parameters. The analysis was conducted for the 48 contiguous United States, and then again for groups of states corresponding to the EPA Regions.

2.0 Approach

The long form of the 1990 census asked the respondents where they got the water for their home. The choices were:

1) a public system such as a city water department or private company;
2) an individual drilled well;
3) an individual dug well; or
4) some other source such as a spring, creek, river, cistern, etc.

The respondents corresponded to a total of 102 million households. Of these households, 84% were served by a public system, 13% were served by an individual drilled well, 1.6% were served by an individual dug well, and 1.0% were served by some other private source. There are far more private wells than there are public water supply wells: 140,000 public water supply systems rely on ground water, but there are over 15 million private drinking water wells in the United States (Toccalino and Hopple, 2010).

Public water supply wells are regularly monitored for water quality. In contrast, private wells are rarely monitored (DeSimone et al., 2009). It is less likely that contamination in private water supplies will be identified and remedied. For this reason, this analysis will focus on private sources of water supply.

There are several lines of evidence that shallow ground water is vulnerable to contamination from underground storage tanks. Squillace et al. (2004) surveyed 518 shallow wells, and compared the detection frequency for the BTEX compounds to the detection frequency reported in earlier studies of urban wells and rural drinking water wells. Averaged across the 518 wells, 1% had concentrations of benzene exceeding 0.2 µg/L. Concentrations of benzene exceeded 0.2 µg/L in 3.2% of urban wells compared to 0.3% of rural wells. Urban wells were ten times more likely to be contaminated with benzene.

In a survey of private domestic wells in the US, 34% contained coliform bacteria and 7.9% contained *Escherichia coli* bacteria (DeSimone et al., 2009). *E. coli* is present in human and animal feces. The presence of coliform bacteria and *E. coli* bacteria in particular are indications of fecal contamination. Plausible sources of fecal contamination are septic tank leach fields, leaking sewer lines, and animal droppings. These sources occur at or above the water table, and will contaminate shallow ground water. The prevalence of fecal contamination in private domestic wells in the US indicates that many of these wells produce water from near the water table. Because motor fuel is lighter than water, releases from USTs also tend to accumulate at the water table. As a result, the shallow ground water is more vulnerable to contamination from a release from a UST. Presumably, private wells that are vulnerable to fecal contamination are also vulnerable to a release from a UST.

Shallow ground water also provides the water to springs and contributes the base flow to small creeks. For the purpose of this analysis, if a respondent to the 1990 census identified their source of drinking water as an individual drilled well, an individual dug well, or some other source such as a spring, creek, river, cistern, etc., their drinking water supply was considered to be vulnerable to contamination by a release of gasoline.

Based on the response from the long form, the 1990 census provided estimates for each census block group for the following categories: Drill_well, Dug_well, and Oth_water. The reported estimates for the numbers of drilled wells, dug wells, and other supplies of water were summed to obtain an estimate of the number of households in each census block group that obtained water from a private source. The 1990 census also reported the surface area [square miles] of each census block group.

A data file was purchased from ESRI Business Solutions (ESRI, 2009) that contained the latitude and longitude of active retail gasoline service stations in the United States. **Figure 1** presents a map of gasoline service stations in the contiguous United States– some 91,308 mapped locations.

The data provided by ESRI may underestimate the number of retail gasoline service stations. A report issued by the Government Accountability Office (GAO, 2011) quoted an estimate that was provided by NPN magazine, a trade magazine that serves the petroleum marketing industry (www.npnweb.com). As reported in NPN *MarketFacts 2010,* there were approximately 159,000 retail fueling outlets in the United States in 2010. In 2005, there were approximately 169,000 retail outlets.

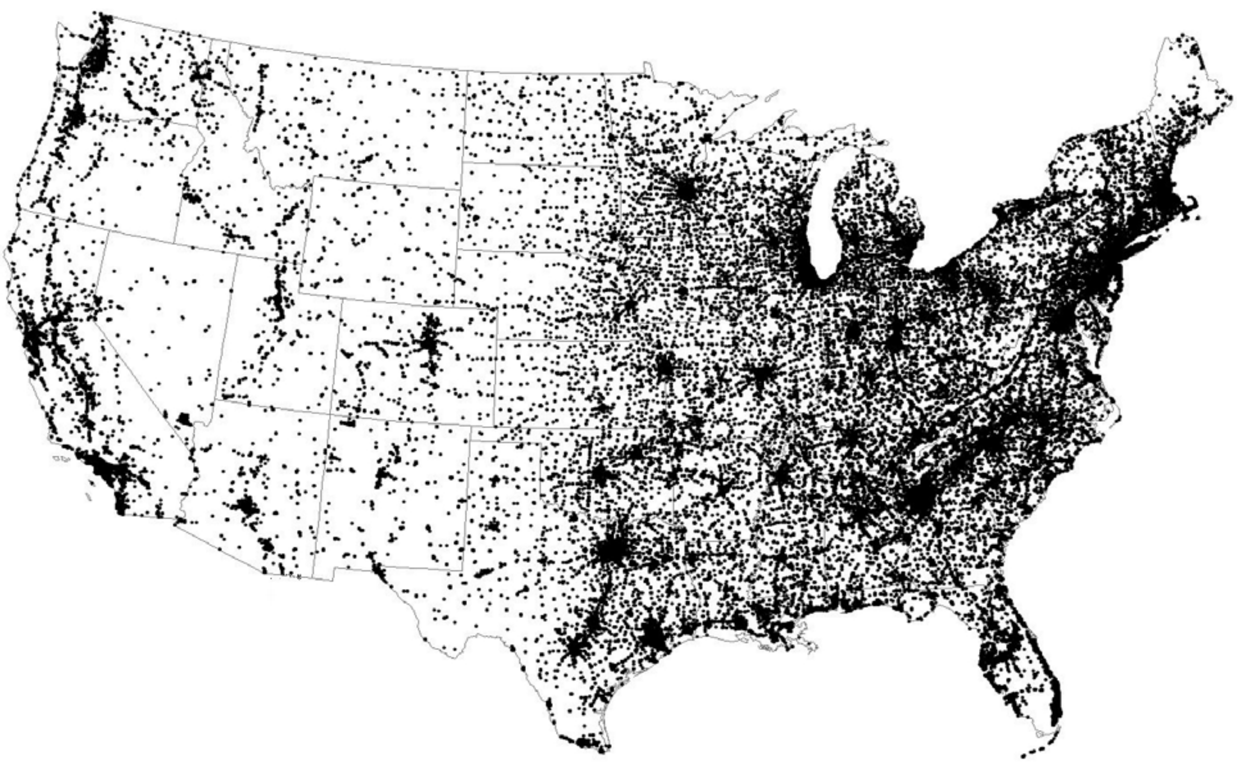


Figure 1. *The location of every active gasoline service station in 2009 – 91,308 Locations (ESRI Business Solutions, 2009).*

These numbers include Alaska and Hawaii, while the 91,308 stations that were mapped by ESRI did not. However, in 2009, Alaska and Hawaii contained only 0.6% of the total population of the United States. In addition, fuel that is stored in USTs that are owned by non-retail facilities such as car rentals, bus depots, and units of government can also pose a risk to ground water resources. This assessment only takes into account the retail gasoline service stations that were contained in the ESRI data file. The ESRI data file may under represent the true number of service stations by as much as one half.

Using Geographical Information System tools (GIS tools) and geo-referenced GIS coverage files on each census block group, the latitude and longitude of each active service station was used to assign the service station to a census block group. Then the number of service stations in each census block group was summed.

A simple probability analysis was performed based on the distribution of service stations and the distribution of the households that obtained water from a private supply. Specifically, GIS was used to compare:

- The relative possibility that an individual household that obtains its water from a private source will be impacted by a release from any service station in the immediate neighborhood;
- The relative possibility that a release from an individual service station will impact any household in the immediate neighborhood that obtains water from a private source;
- The relative possibility for a given surface area of land that there will be an impact from any service station to any household that obtains its water from a private source.

Figure 2 presents a map showing the distribution of households whose primary source of drinking water comes from private sources. This was obtained from 1990 US Census statistics, which is the last census that reported this data. Each dot on this map represents 10,000 households that obtained water from private sources.

Figure 3 presents the 1990 US Census Tract Areas (block groups).   This map of the 1990 Census block groups provides a geographic canvass which can serve as a normalizing factor that allows for a simple probability analysis based on areal distribution and densities. This simple probability analysis yields an **Index of Vulnerability** that can be displayed on a map.

The number of 1990 US Census block groups shown in **Figure 3** totals 226,320. Each is represented by an individual closed polygon. This is a very large number of polygons on which to perform even simple mathematical calculations in a GIS application. It was therefore prudent to simplify the analysis by reducing the total number of pertinent census block groups. This was done by superimposing the locations of gasoline service stations and the locations of households of people who drink water from private sources onto the census block groups coverage and then dropping out those census block groups that <u>did not</u> contain at least one household with people who drink water from a private source and one service station. This left 33,167 census block groups on which to perform the analysis.

Depending on population density, census block groups vary widely in size. **Figure 4** presents the frequency distribution of the surface areas for all 226,320 census block groups. **Figure 5** presents a map of the 33,167 census block groups that contain <u>both</u> households that consume water from

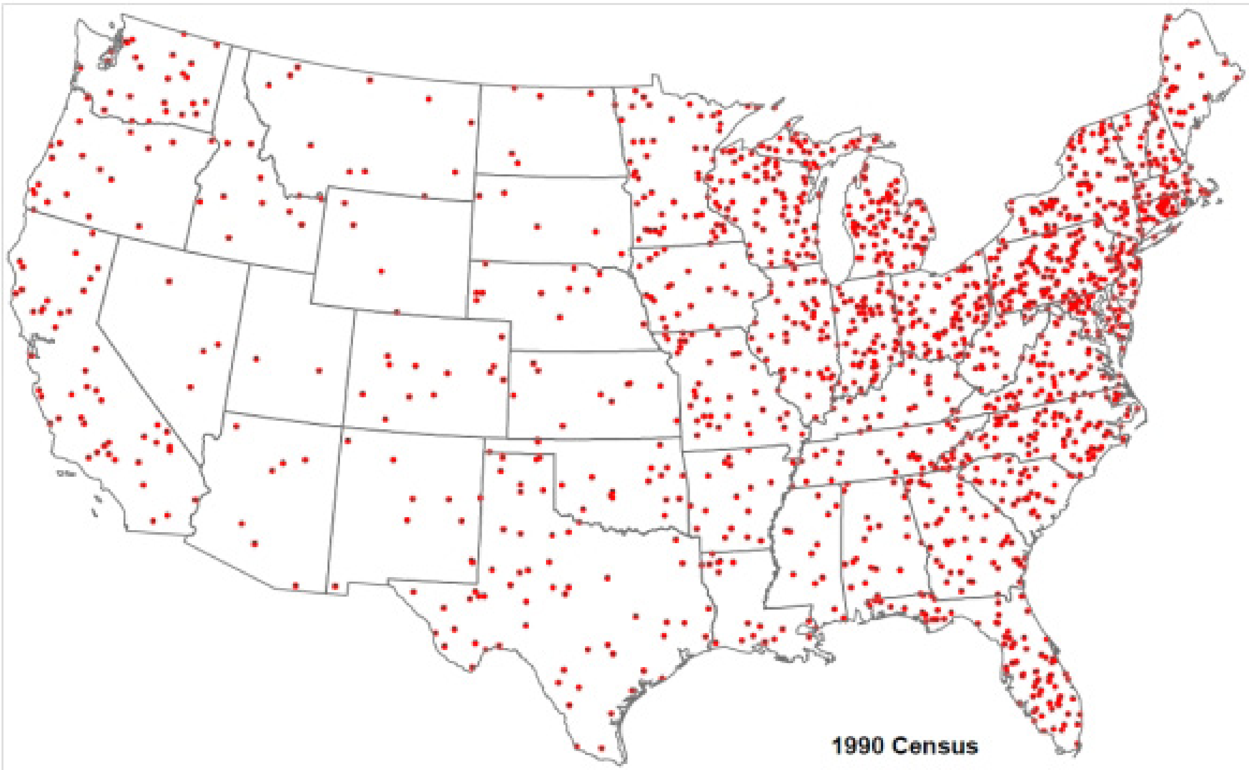


Figure 2. *The distribution of households with private wells. Each dot represents 10,000 households.*

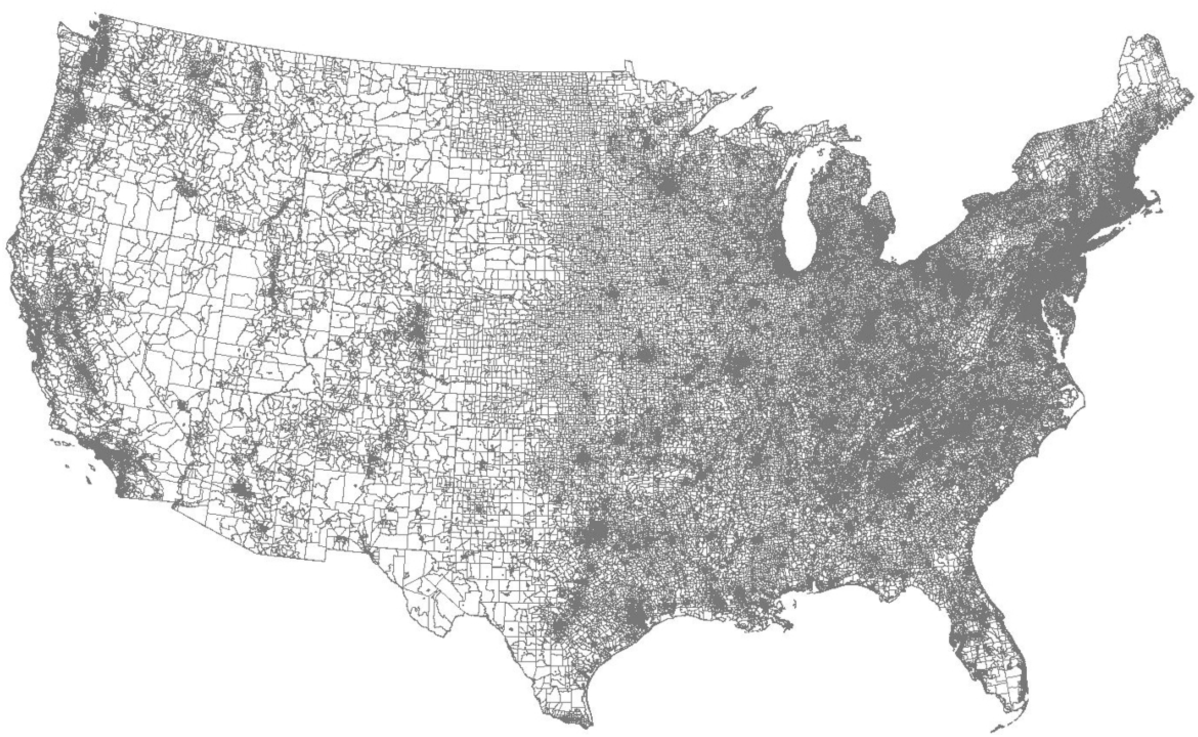


Figure 3. *All 1990 US Census Block Groups – 226,320 block groups.*

private sources and gasoline service stations. **Figure 6** presents the frequency distribution of the surface areas of the census block groups that contain both households that obtain water from private sources and gasoline service stations. The distributions in **Figure 4** and **Figure 6** are significantly different because people who drink water from a private source are more likely to live in a rural area where the census block group is larger. The median surface area of all census block groups is 0.41 square miles. The median surface area of the census block groups that contain both households that consume water from private sources and gasoline service stations is 5.0 square miles.

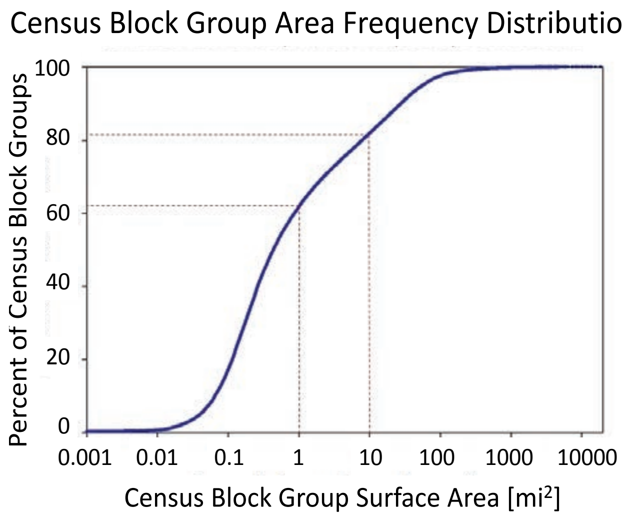


Figure 4. *Frequency distribution of the surface area of all census block groups.*

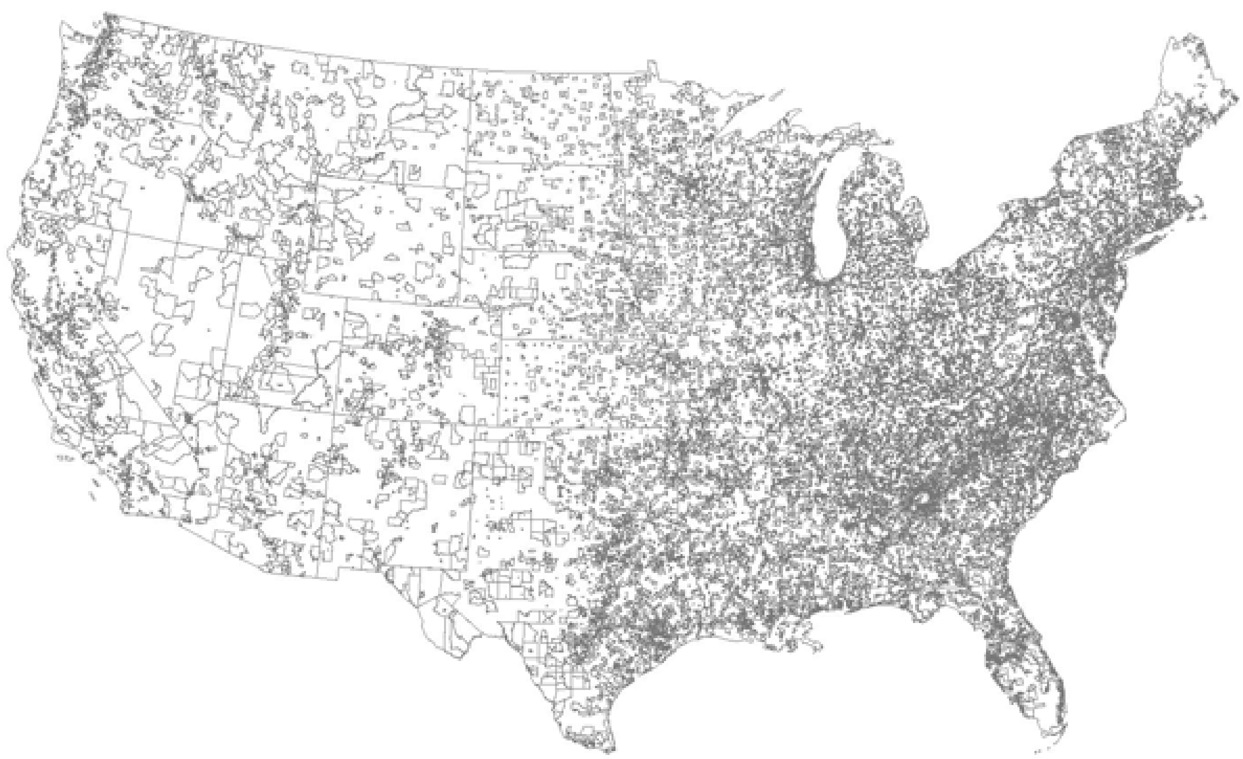


Figure 5. *1990 US Census Block Groups Containing BOTH People Drinking Water from a Private Source and Gasoline Service Stations – 33,167 block groups.*

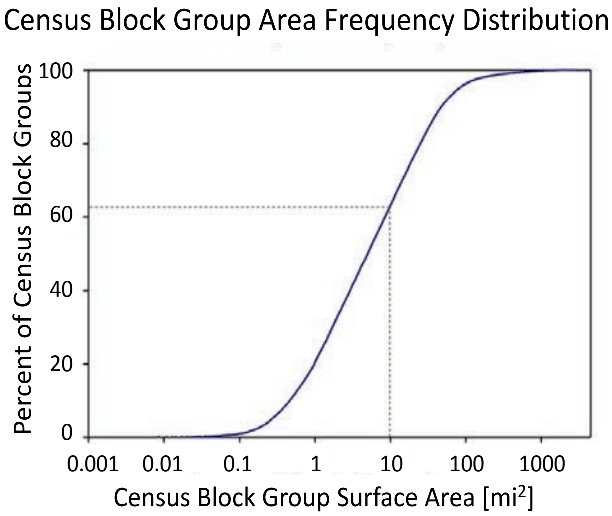


Figure 6. *Frequency distribution of the surface area of those census block groups that contain at least one service station and at least one household that obtains water from a private source.*

With these GIS coverages in place, three separate indices were calculated. Each index was calculated for those census block groups that had at least one service station and at least one household that obtained water from a private source.

Vulnerability Index 1 is simply the density of service stations in each census block group. It is calculated as the number of service stations in each census block group divided by the area of each census block in square miles. It provides an estimate of the possibility that the water supplied to a household from a private source will be impacted by a service station. **Vulnerability Index 1** describes the consumer's risk of having his water supply impacted. The higher the calculated index, the higher the vulnerability.

Table 1 compares the distribution of calculated values for **Vulnerability Index 1** for the upper 30%, the upper 10%, the upper 3% and the upper 1% of all values in the 48 contiguous states and in each EPA Region. The values of the vulnerability index were calculated from data on the census blocks groups in the 48 contiguous states as a whole, and then the values were ranked to identify the maximum value and the lowest value in the upper 1%,

Table 1. Range of numerical values calculated for Vulnerability Index 1 [service stations per square mile].

Area	Maximum Value	Lowest Value in:			
		Upper 1%	Upper 3%	Upper 10%	Upper 30%
48 States	201	11.6	6.9	3.0	0.84
EPA Region 1	36	13.6	7.6	3.5	1.06
EPA Region 2	201	32.6	17.5	6.3	1.84
EPA Region 3	46	12.2	7.0	3.1	0.88
EPA Region 4	58	7.5	4.5	2.0	0.59
EPA Region 5	46	10.6	7.1	3.1	0.97
EPA Region 6	55	9.0	5.4	2.5	0.65
EPA Region 7	23	5.4	3.1	1.1	0.32
EPA Region 8	22	8.4	5.8	2.3	0.39
EPA Region 9	82	15.7	10.5	5.4	1.91
EPA Region 10	19	7.7	5.6	2.6	0.93

3%, 10% and 30% of all values. Then the values were calculated and ranked for the census block groups in each individual EPA Region.

Vulnerability Index 1 was highest in EPA Region 2 and lowest in EPA Regions 7, 8 and 10.

Vulnerability Index 2 is simply the density of households in each census block group that obtain water from a private source. It is calculated as the number of households in each census block group that obtain water from a private source divided by the surface area of the block group in square miles. It provides an estimate of the possibility that a release from a particular service station will impact the water supplied to a household that obtains water from a private source. **Vulnerability Index 2** describes the risk to the service station owner that a release from his station will impact someone's private water supply. The higher the calculated index, the higher the vulnerability.

Table 2 compares the distribution of calculated values for **Vulnerability Index 2** in the 48 contiguous states and in each EPA Region. As was done previously, **Vulnerability Index 2** was calculated and ranked for census block groups in the 48 states as a whole, and then again for each individual EPA Region. **Vulnerability Index 2** was highest in Region 5 and lowest in Region 7.

To describe the risk to the entire community that obtains ground water from shallow sources, the index that describes the possibility that a single household might be impacted was multiplied by the number of households that are at risk. **Vulnerability Index 3** was calculated by multiplying **Vulnerability Index 1** for each block group by the number of households in each block group that obtain water from a private source. **Vulnerability Index 3** describes the resource manager's risk that a release from a gasoline service station in their geographic area will impact the private

Table 2. Range of numerical values calculated for Vulnerability Index 2 [households obtaining water from a private source per square mile].

Area	Maximum Value	Lowest Value in:			
		Upper 1%	Upper 3%	Upper 10%	Upper 30%
48 States	2191	361	189	81	29
EPA Region 1	1251	337	207	107	43
EPA Region 2	2051	531	345	140	55
EPA Region 3	1432	331	162	83	37
EPA Region 4	1545	347	169	68	24
EPA Region 5	2191	498	266	111	38
EPA Region 6	698	210	111	46	14
EPA Region 7	488	100	56	24	9
EPA Region 8	797	140	81	30	8
EPA Region 9	626	306	191	89	32
EPA Region 10	808	233	138	67	27

water supply of a household in their geographic area. The higher the calculated index, the higher the vulnerability.

Table 3 compares the distribution of calculated values for **Vulnerability Index 3** in the 48 contiguous states and in each EPA Region. As was done previously, **Vulnerability Index 3** was calculated and ranked for census block groups in the 48 states as a whole, and then again for each individual EPA Region. **Vulnerability Index 3** was highest in Region 2 and lowest in Regions 7 and 8.

Table 3. Range of numerical values calculated for Vulnerability Index 3 [service stations per square mile multiplied by the number of households obtaining water from a private source].

Area	Maximum Value	Lowest Value in:			
		Upper 1%	Upper 3%	Upper 10%	Upper 30%
48 States	*4213*	*547*	*286*	*120*	*41*
EPA Region 1	*1429*	*541*	*310*	*154*	*59*
EPA Region 2	*4213*	*970*	*516*	*202*	*78*
EPA Region 3	*3811*	*524*	*258*	*122*	*52*
EPA Region 4	*2678*	*538*	*253*	*110*	*37*
EPA Region 5	*2191*	*704*	*368*	*156*	*52*
EPA Region 6	*1118*	*354*	*172*	*71*	*21*
EPA Region 7	*975*	*160*	*87*	*35*	*12*
EPA Region 8	*836*	*223*	*127*	*46*	*11*
EPA Region 9	*2418*	*420*	*265*	*128*	*44*
EPA Region 10	*2540*	*394*	*230*	*104*	*39*

3.0
Results and Discussion

The appendices contain maps that depict the distribution of each of the **Vulnerability Indices.** Maps are provided showing the distribution of block groups with values for the **Indices** that are in the upper 30%, upper 10%, upper 3%, and upper 1% of all block groups in the map. Maps are provided for the 48 contiguous United States as a whole, and for those contiguous States that are contained within each EPA Region.

This analysis provides a screening approach to identify those areas in the US where ground water that is used for drinking water is most at risk from UST releases. These areas are at the greatest risk for potential impacts.

As an example, **Figure 7** depicts the distribution across the US of those census block groups that fall within the highest 30% of all census block groups for **Vulnerability Index 3**. Those census block groups are colored blue and give a visual distribution of those areas in the United States that are more vulnerable from the point of view of a resource manager. The most vulnerable census block groups are concentrated in the suburban fringe around major cities. This relationship is even more apparent at smaller scale in figures in the Appendix. See **Figure 8** for an example.

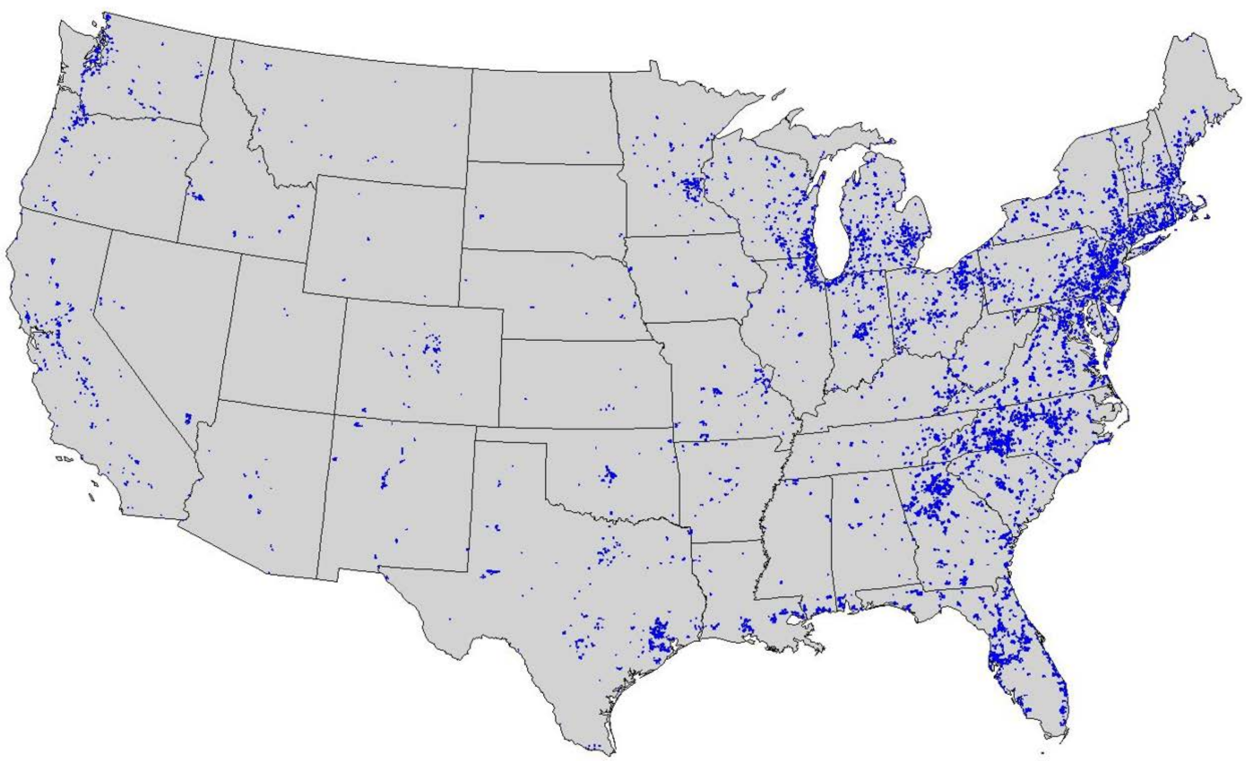


Figure 7. *Locations of census block groups where the value of **Vulnerability Index 3** is in the upper 30% of all census block groups. This is the resource manager's risk of an impact.*

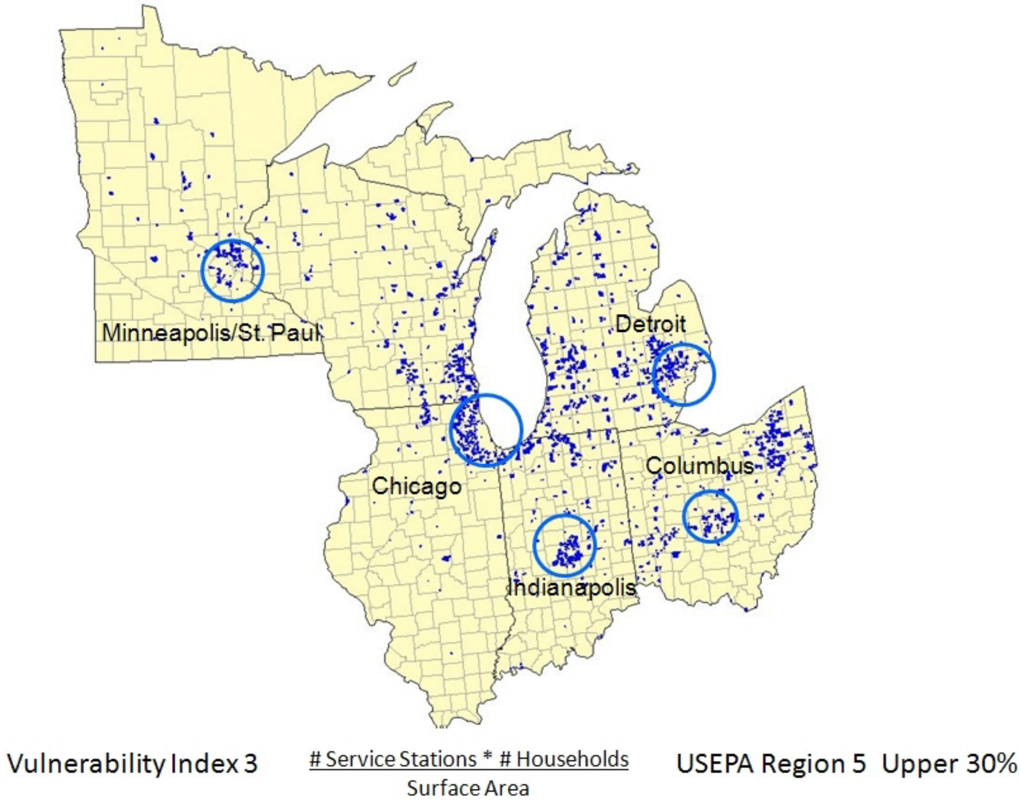


Figure 8. *Figure from Appendix F showing higher vulnerability in suburbs of Minneapolis-St Paul, MN, Chicago, IL, Indianapolis, IN, Columbus, OH and Detroit, MI.*

The indices are based on only two environmental parameters; and one of the parameters describes the situation in 1990. As a result, the indices can only provide a screening level assessment of the risk to water supply. The predictive value of the approach is illustrated in **Figure 9.** Ayotte et al. (2008) published information on the distribution of MTBE in ground water in New Hampshire. The most plausible source of MTBE in ground water in New Hampshire is leaks of motor fuel from underground storage tanks.

Figure 9 compares the distribution of ground water contamination from MTBE to the distribution of **Vulnerability Index 1, Vulnerability Index 2** and **Vulnerability Index 3.** In New Hampshire, there was little difference in the distribution of MTBE contamination between public wells and private wells. This may be due, in part, to the fact that most public and private wells produce water from fractured rock aquifers. In general, there is fair agreement between the locations with high vulnerability and the locations with actual impacts to water supply wells; however, the spatial correlations are far from perfect. For New Hampshire, the distribution of **Vulnerability Index 1** (the density of service stations) and **Vulnerability Index 2** (the density of households obtaining water from private sources) were similar. However, **Vulnerability Index 3** (the product of the density of service stations and the number of households obtaining water from private sources) had the strongest spatial association with the actual distribution of MTBE contamination in drinking water wells.

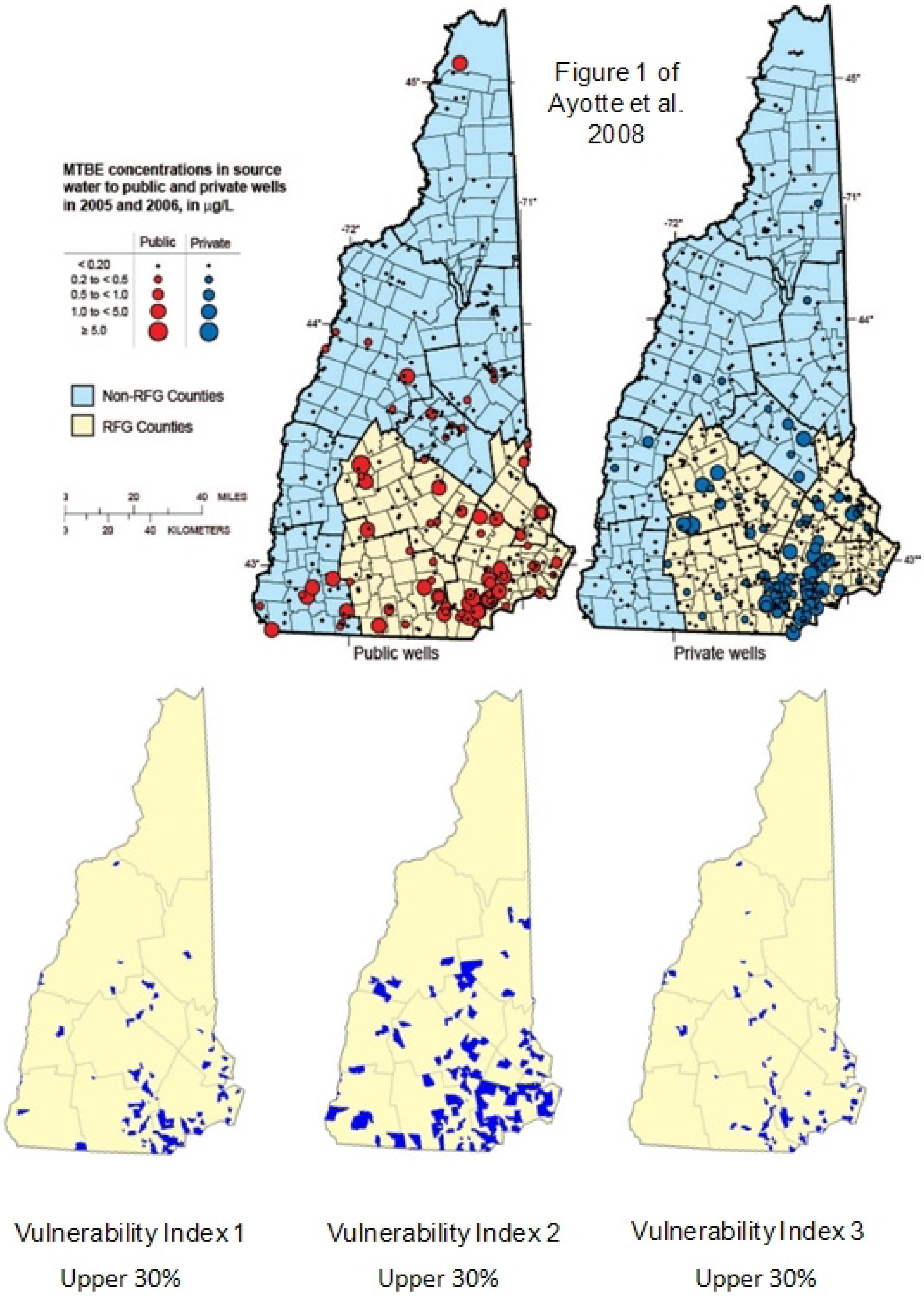


Figure 9. *Comparison between the distribution of MTBE contamination in water supply wells in New Hampshire and the estimate of Vulnerability from Indices 1, 2 and 3.*

This screening approach can assist communities and States in identifying those localities that are particularly vulnerable. Additionally, the approach can serve as a useful tool for communities as they develop plans for sustainable water supply. These plans will be especially valuable as population growth in the US creates increasing demands for water.

A simple comparison of vulnerabilities on a local and regional scale is a first step toward an integrated approach that will allow communities to balance growth in the demand for ground water against the cost to protect existing supplies from contamination, or the cost to reclaim ground water that is already contaminated.

This study is one example of how vulnerability can be assessed. Other GIS-based vulnerability assessments could be done in a similar manner considering other pathways for exposure such as vapor intrusion. Further improvements in such assessments will require more detailed understanding of the geological context, the local climate, and other features of the landscape.

The maps of vulnerability indices that are provided in this document are organized by U.S. EPA Regions. At this scale, it can be difficult to associate the census block groups used to calculate the indices with political boundaries. If an employee of a regulatory agency in any state, territory, county, city, or Native American government desires maps that present the indices for the geographic area that is of particular concern to them, they should request support from the Ground Water Technical Support Center, Ground Water and Ecosystems Restoration Division (U.S. EPA). The request can be made to the Center Director, Dr. David Burden, by email at *burden.david@epa.gov* or by telephone at 580-436-8606. The request should mention the indices that are requested, and the political boundaries that are included.

4.0
Future Directions

One of the peer reviewers provided the following warning. Their agency

> **…** *recently started an UST/LUST Risk Project in which we* [the state agency] *are identifying USTs with a high probability of leaking that are located in environmentally sensitive areas. Our initial efforts attempted to use "big picture" databases for our analysis, such as what you have done. However, we have found that this approach can produce false negatives, i.e., it can identify UST facilities as low risk, when in reality, they are high risk. This can be a major problem for UST/LUST resource managers.*

The next step will require tools to understand the movement and redistribution of contaminated ground water that might impact water supply wells, distance to receptor, and facility specific criteria such as overfill protection, spill containment, cathodic protection, etc. As an example of such a tool, the state of New Mexico has built a GIS system called Geographic Information System Screening Tool of New Mexico, or GoNM (Pruett and Arfman, 2011). The tool incorporates information on:

1) the physical surroundings of the facility, including factors such as the geology of the aquifer, the depth to ground water, and soil permeability;
2) United States Census data including population density, and
3) technical features of each UST facility, such as the composition of the underground storage tank, how the piping was constructed, the presence of secondary containment, the type of overfill protection, the method used to detect leaks, the age and capacity of the tanks, the type of cathodic protection if needed, and the history of Notices of Violations.

The New Mexico Petroleum Storage Tank Bureau uses GoNM to optimize their resources. The tool is used to rate UST facilities based on the chance that they might have a release. The ratings are used to prioritize inspections. The facilities with the highest risk are inspected more often. The tool is also used to identify remedial technology that has been successful at similar locations.

Understanding the interaction between the supply of ground water, and the evolving demand for water at both spatial and temporal scales will help to ensure adequate and safe water supplies for the future. The U.S. EPA and USGS are working to move this understanding from the national and regional scale illustrated in this assessment to the local scale where decisions are made about ground water supply, UST siting, and regulatory inspection and clean-up prioritization.

5.0
References

Ayotte, J.D., D.M. Argue, F.J. McGarry, J.R. Degnan, L. Hayes, S.M. Flanagan and D.R. Helsel. Methyl *tert*-Butyl Ether (MTBE) in public and private wells in New Hampshire: occurrence, factors, and possible implications. *Environmental Science & Technology* 42: 677-684 (2008).

Corseuil, H.X., A.L. Monier, M. Fernandes, M.R. Schneider, C.C. Nunes, M. do Rosario, and P.J.J. Alvarez. BTEX plume dynamics following an ethanol blend release: geochemical footprint and thermodynamic constraints on natural attenuation. *Environmental Science & Technology* 45: 3422-3429 (2011).

DeSimone, L.A., P.A. Hamilton, and R.J. Gilliom. Quality of water from domestic wells in principal aquifers of the United States, 1991-2004—Overview of major findings: U.S. Geological Survey Circular 1332, 48 p. (2009). Available: http://pubs.usgs.gov/circ/circ1332/

GAO Report. BIOFUELS – Challenges to the transportation, sale, and use of intermediate ethanol blends. GAO-11-513. (June 2011). Available: http://www.gao.gov/new.items/d11513.pdf

ESRI Business Solutions. (2009). T2009 Methodology Statement: ESRI Data—Business Locations and Business Summary: All Business Locations-SIC Code-5514, Gasoline Service Stations. Available: http://www.esri.com/industries/retail/index.html

Mackay, D.M., N.R. de Sieyes, M.D. Einarson, K.P. Feris, A.A. Pappas, I.A. Wood, L. Jacobson, L.G. Justice, M.N. Noske, K.M. Scow, and J.T. Wilson. Impact of ethanol on the natural attenuation of benzene, toluene, and o-xylene in a normally sulfate-reducing aquifer. *Environmental Science & Technology* 40: 6123-6130 (2006).

Pruett, J. and S. Arfman. The GISST of GoNM. L.U.S.T. Line Bulletin 68, June 2011, pages 1-4 (2011). Available: http://www.neiwpcc.org/lustline

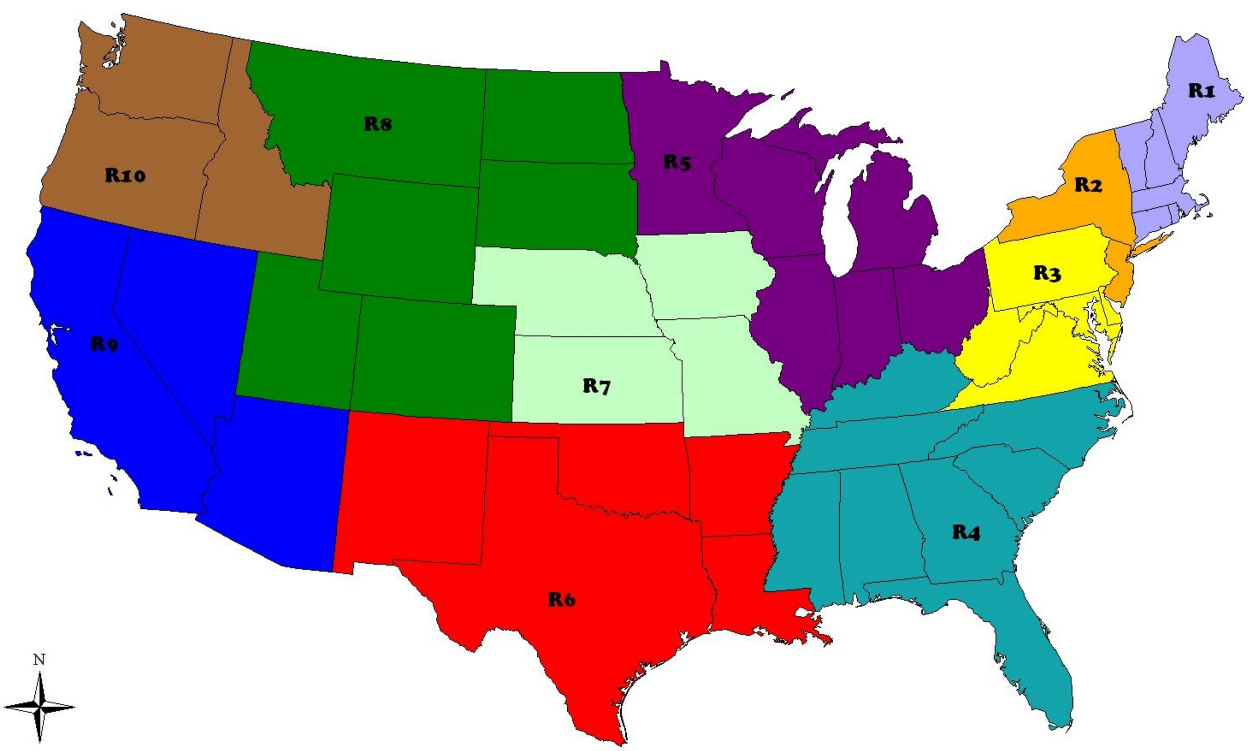
Squillace, P.J., M.J. Moran, and C.V. Price. VOCs in shallow groundwater in new residential/commercial areas of the United States. *Environmental Science & Technology* 38:5327-5338 (2004).

Toccalino, P.L., and J.A. Hopple. The quality of our Nation's waters – Quality of water from public-supply wells in the United States, 1993-2007 – Overview of major findings: U.S. Geological Survey Circular 1346, 58 p. (2010). Available: http://pubs.usgs.gov/circ/1346/

United States 1990 Census Data. (1990). Available: http://www.census.gov/

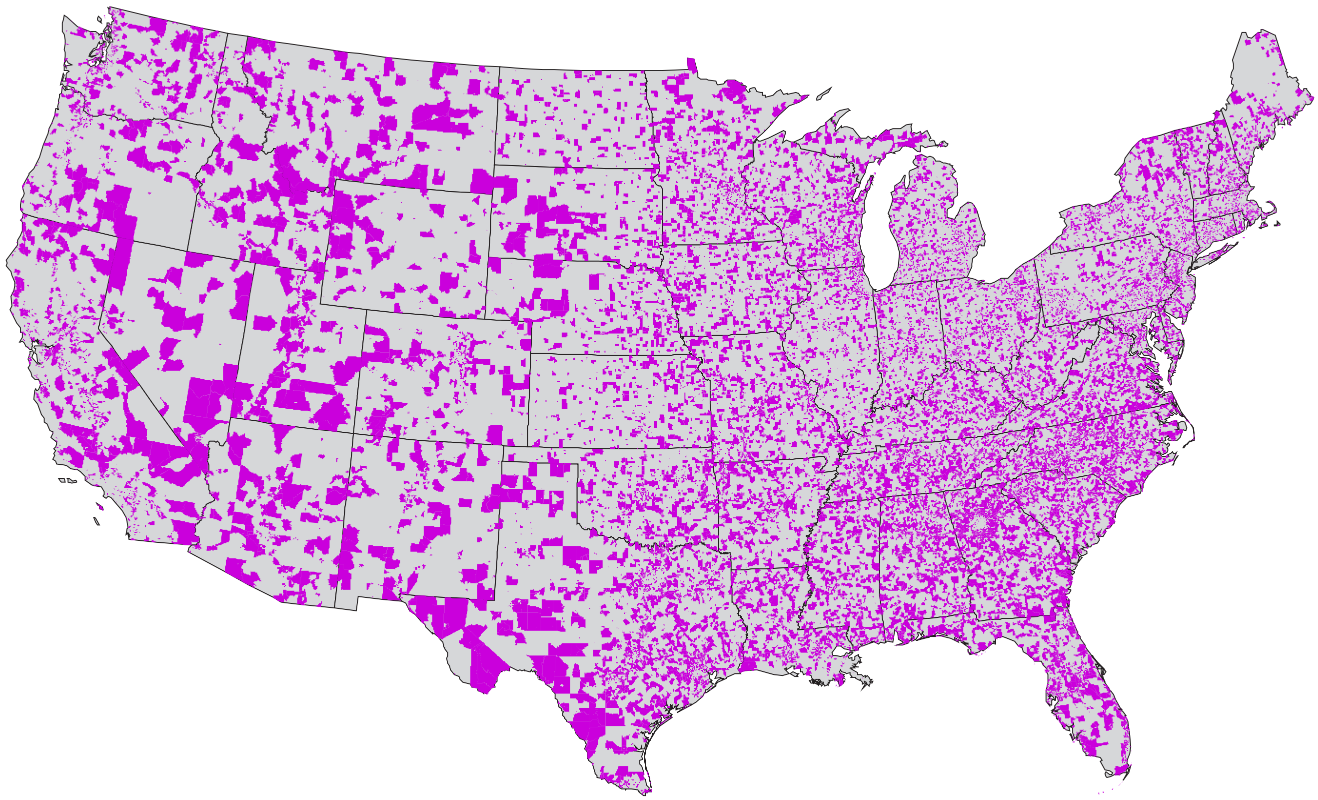
Zogorski, J.S., J.M. Carter, T. Ivahnenko, W.W. Lapham, M.J. Moran, B.L. Rowe, P.J. Squillace and P.L. Toccalino. The quality of our Nation's waters – Volatile organic compounds in the Nation's ground water and drinking-water supply wells: U.S. Geological Survey Circular 1292, 101 p. (2006). Available: http// pubs.usgs.gov/circ1292/

6.0
List of Appendices

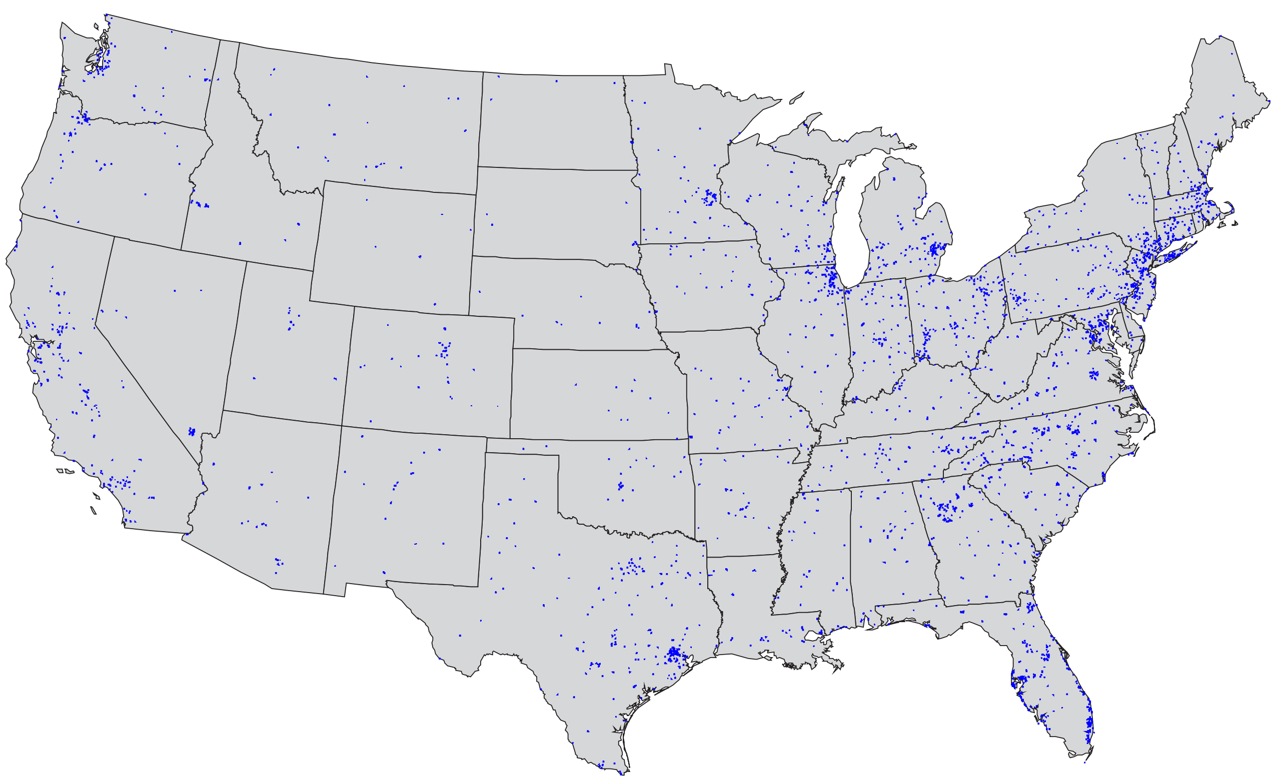


Appendix A

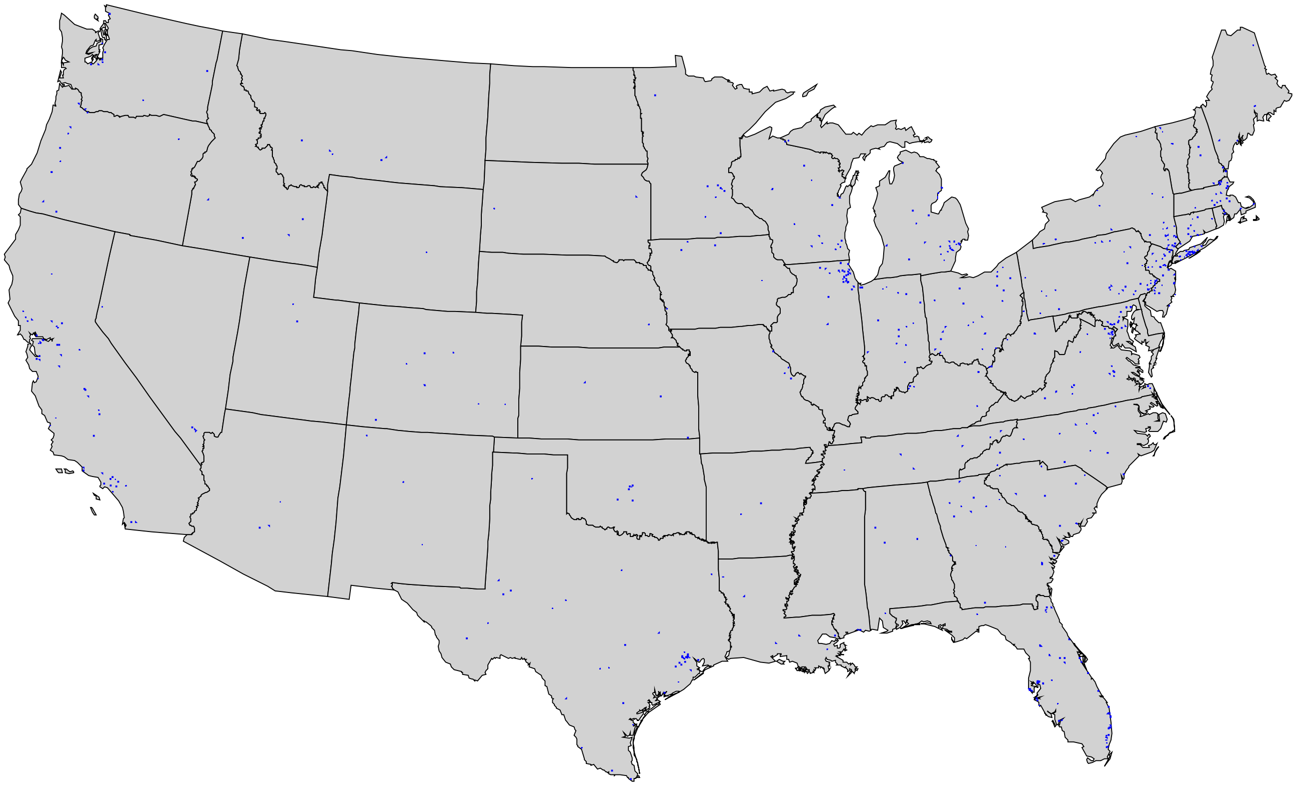
USA 48 States Vulnerability



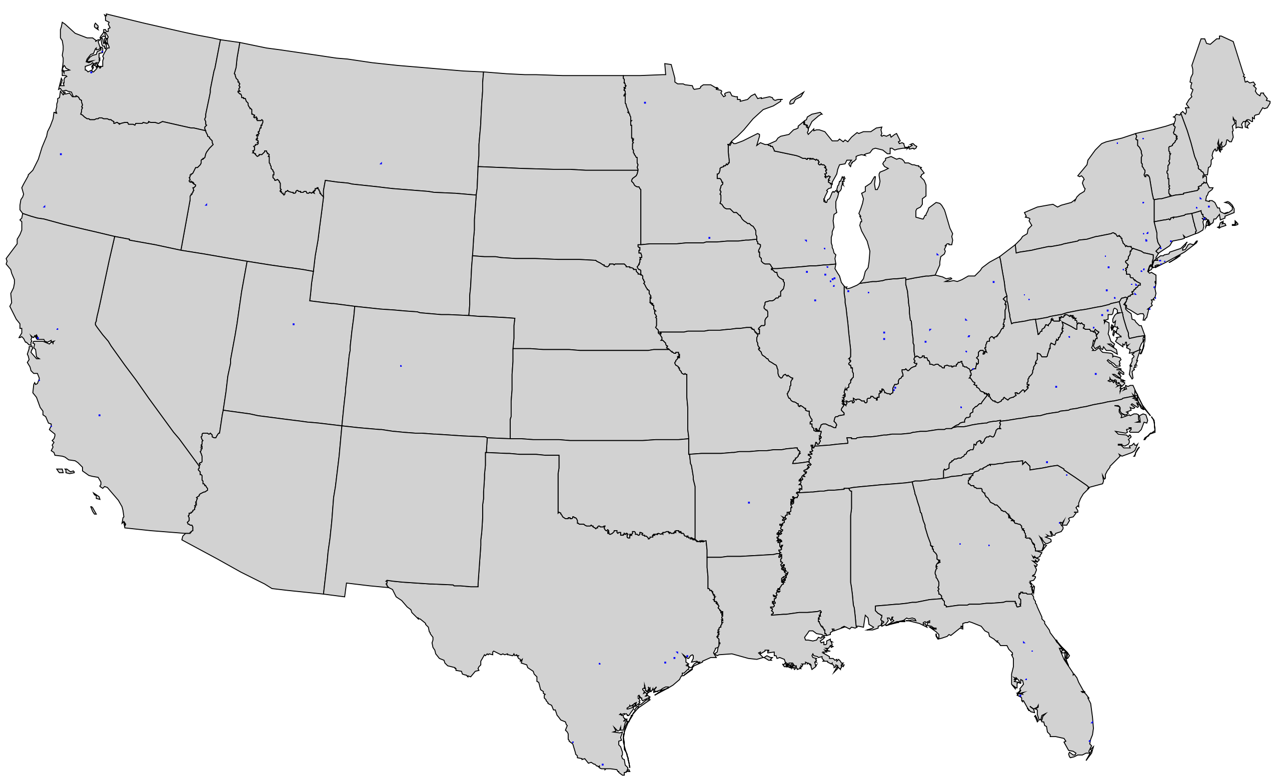
1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water AND Service Stations



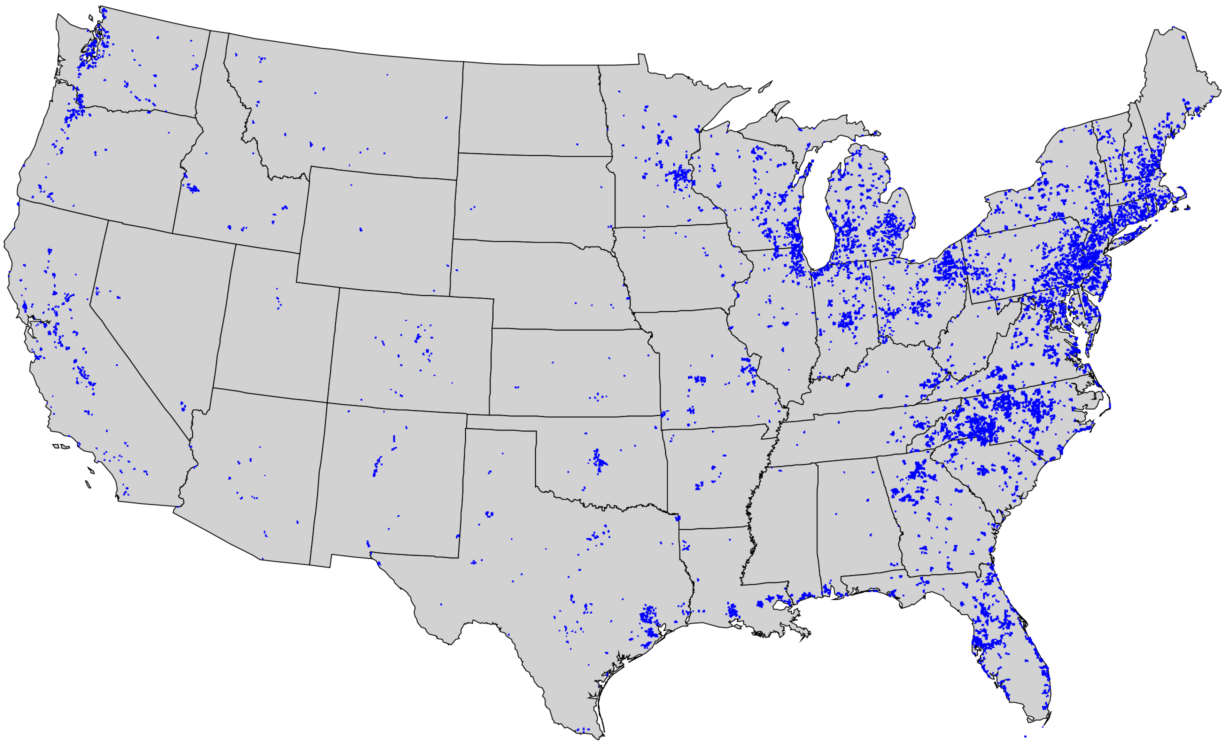
Vulnerability Index 1: Density of Service Stations (stations per square mile) USA: Upper 30%



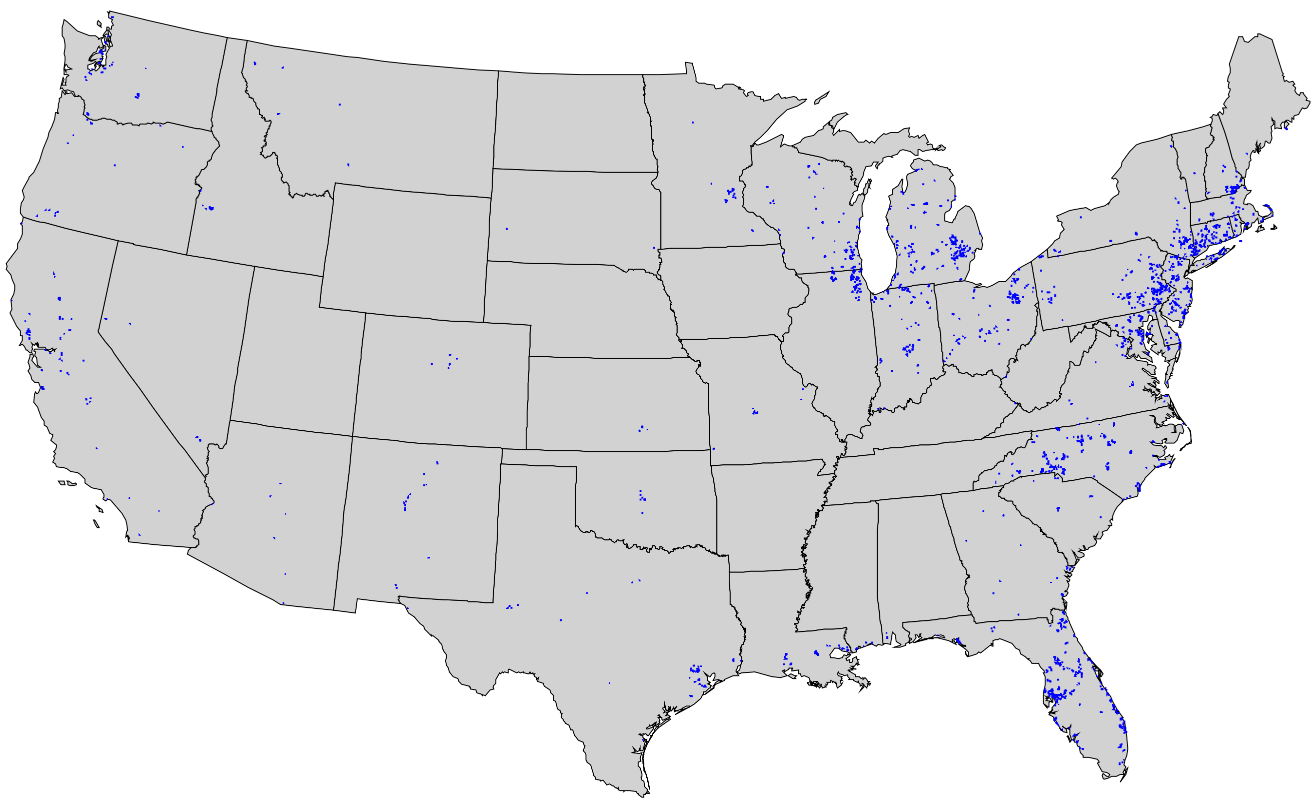
Vulnerability Index 1: Density of Service Stations (stations per square mile) USA: Upper 10%



Vulnerability Index 1: Density of Service Stations (stations per square mile) USA: Upper 3%



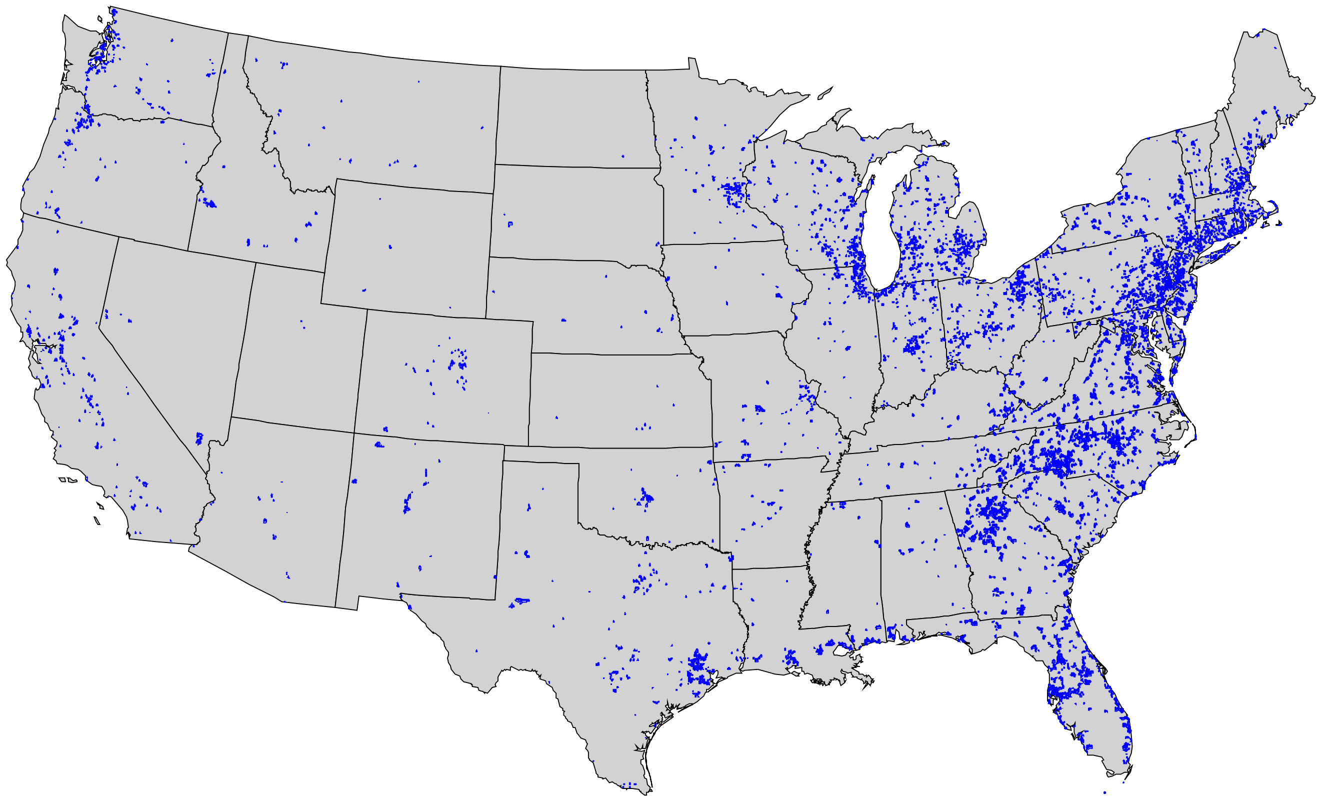
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile) USA: Upper 30%



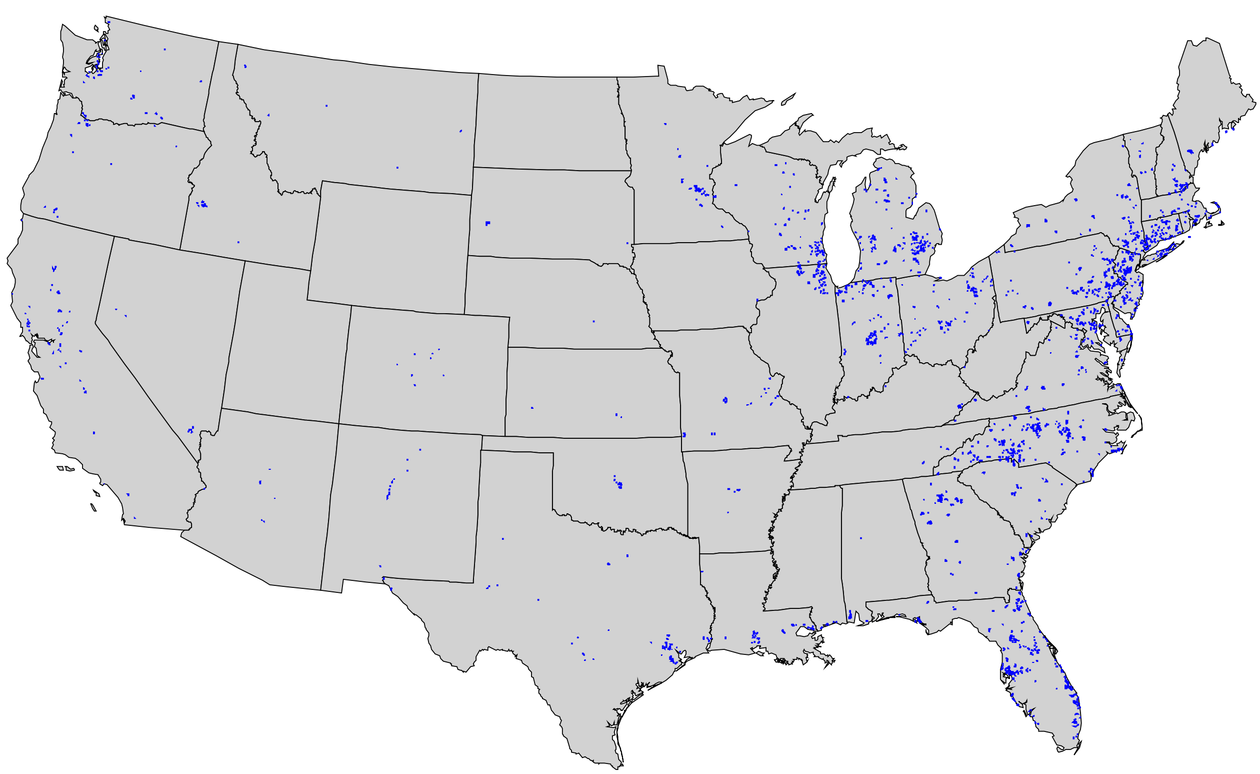
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile) USA: Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile) USA: Upper 3%

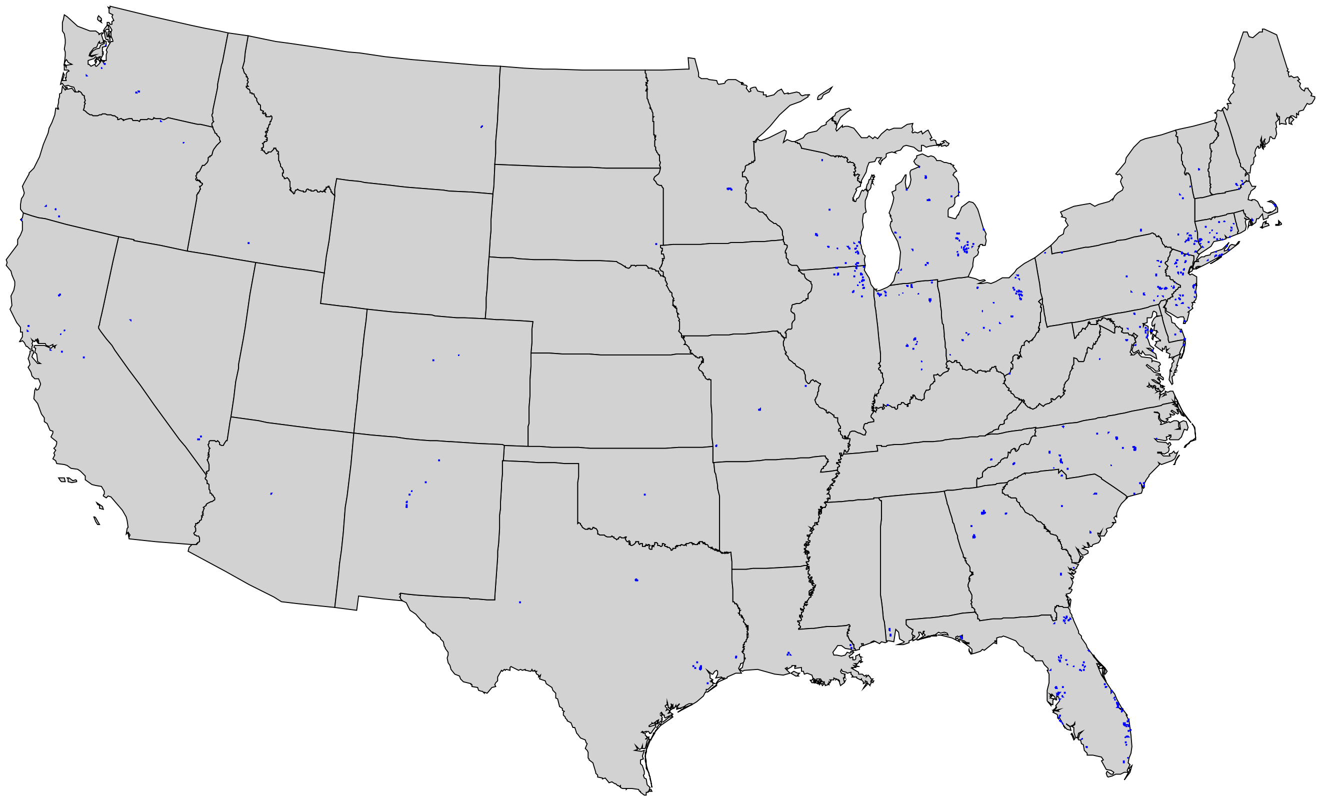
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile) USA: Upper 1%



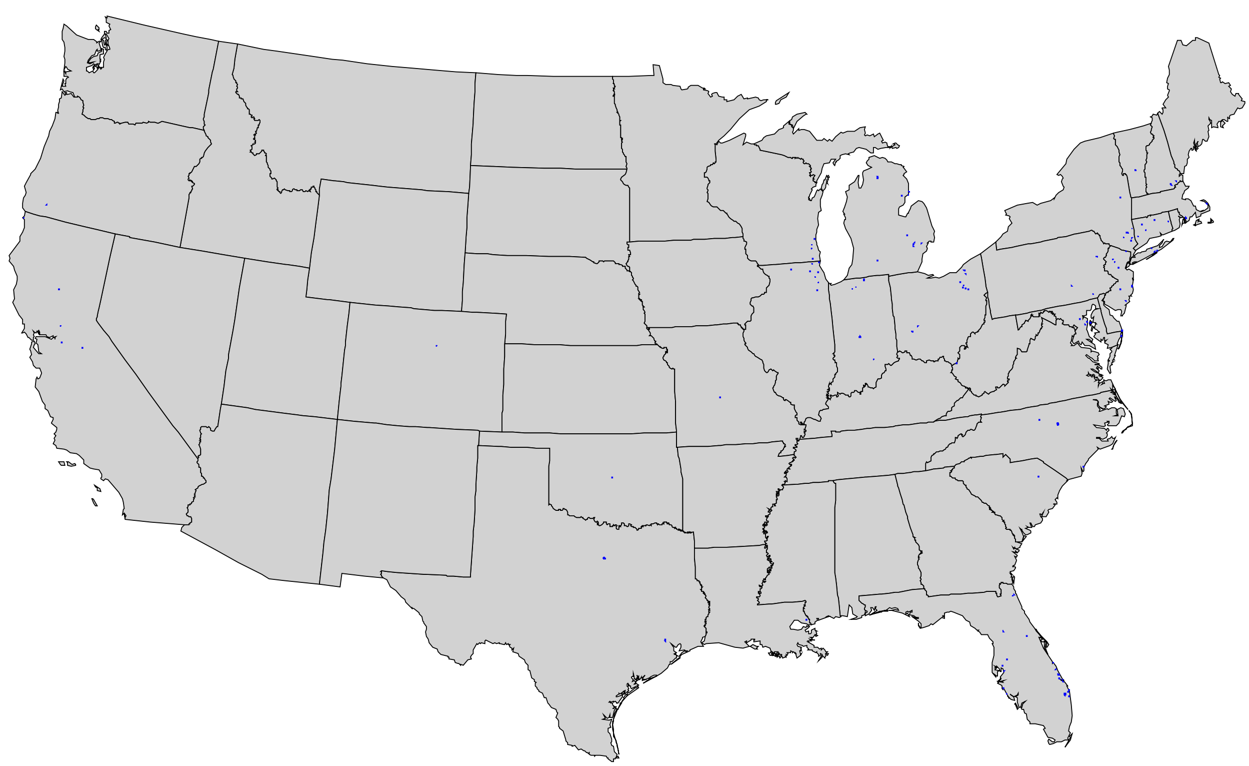
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USA: Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USA: Upper 10%



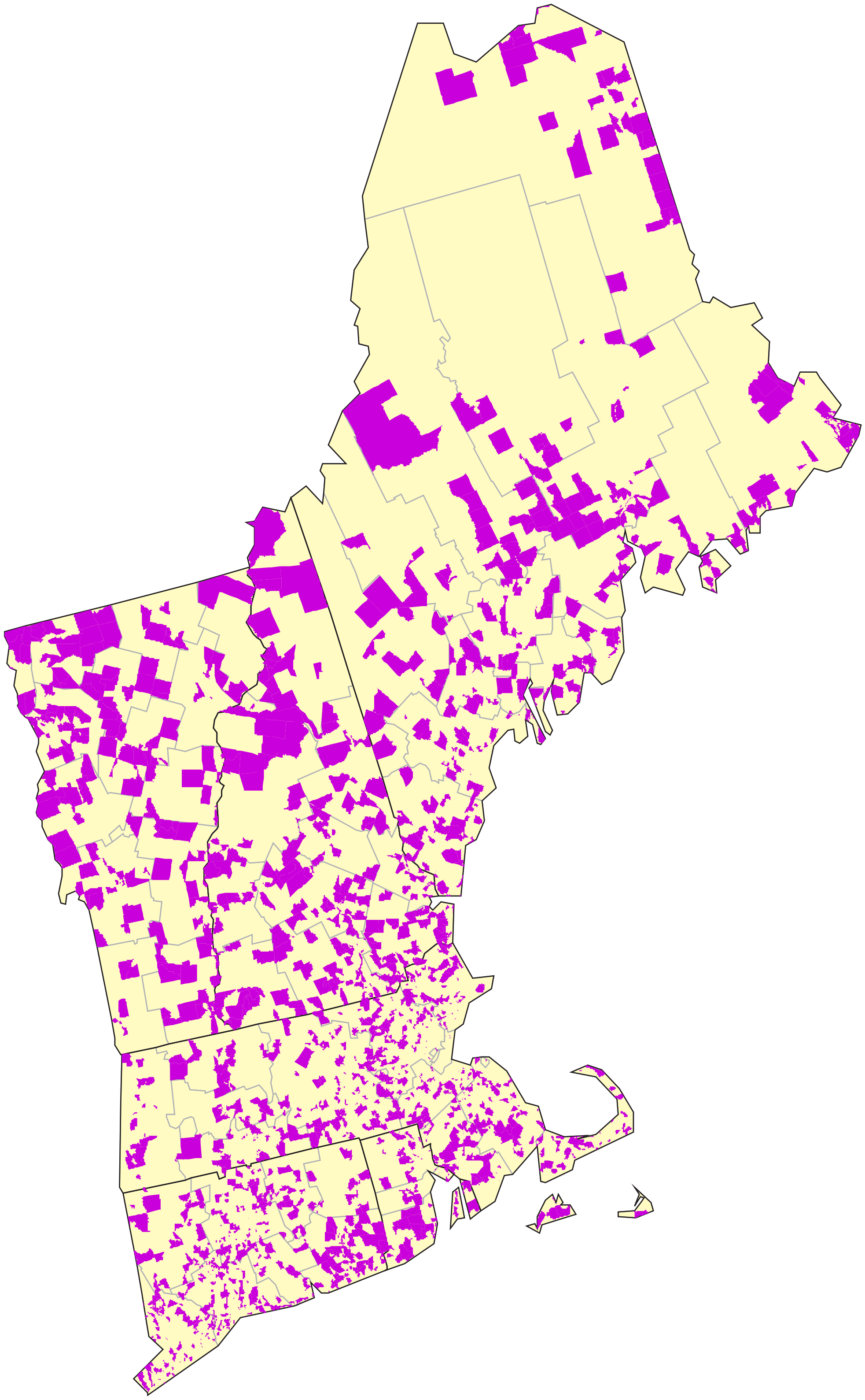
Vulnerability Index 3: $\frac{\#\ \text{Service Stations} * \#\ \text{Households}}{\text{Surface Area}}$ USA: Upper 3%



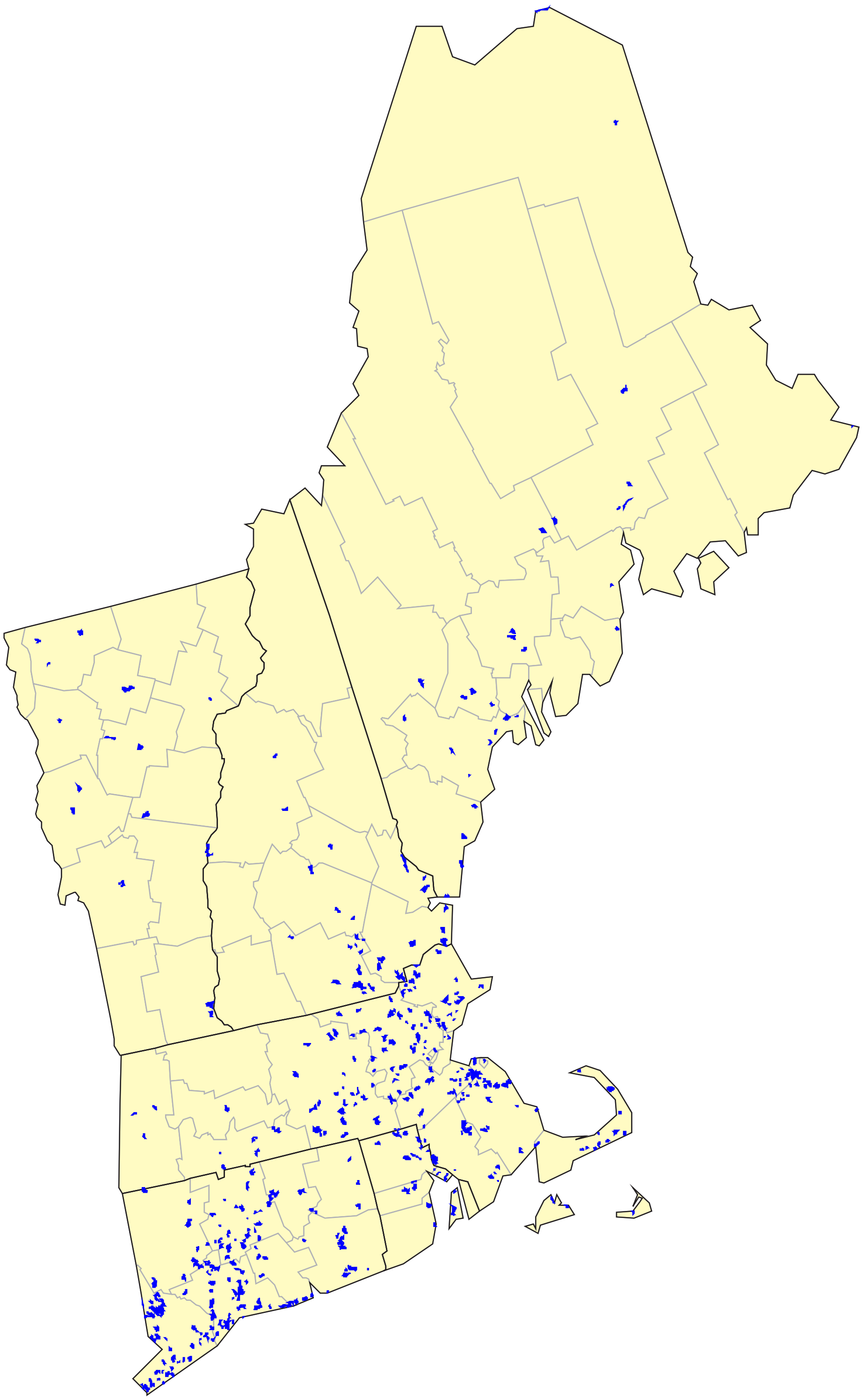
Vulnerability Index 3: $\frac{\#\ \text{Service Stations} * \#\ \text{Households}}{\text{Surface Area}}$ USA: Upper 1%

Appendix B

USEPA Region 1 Vulnerability

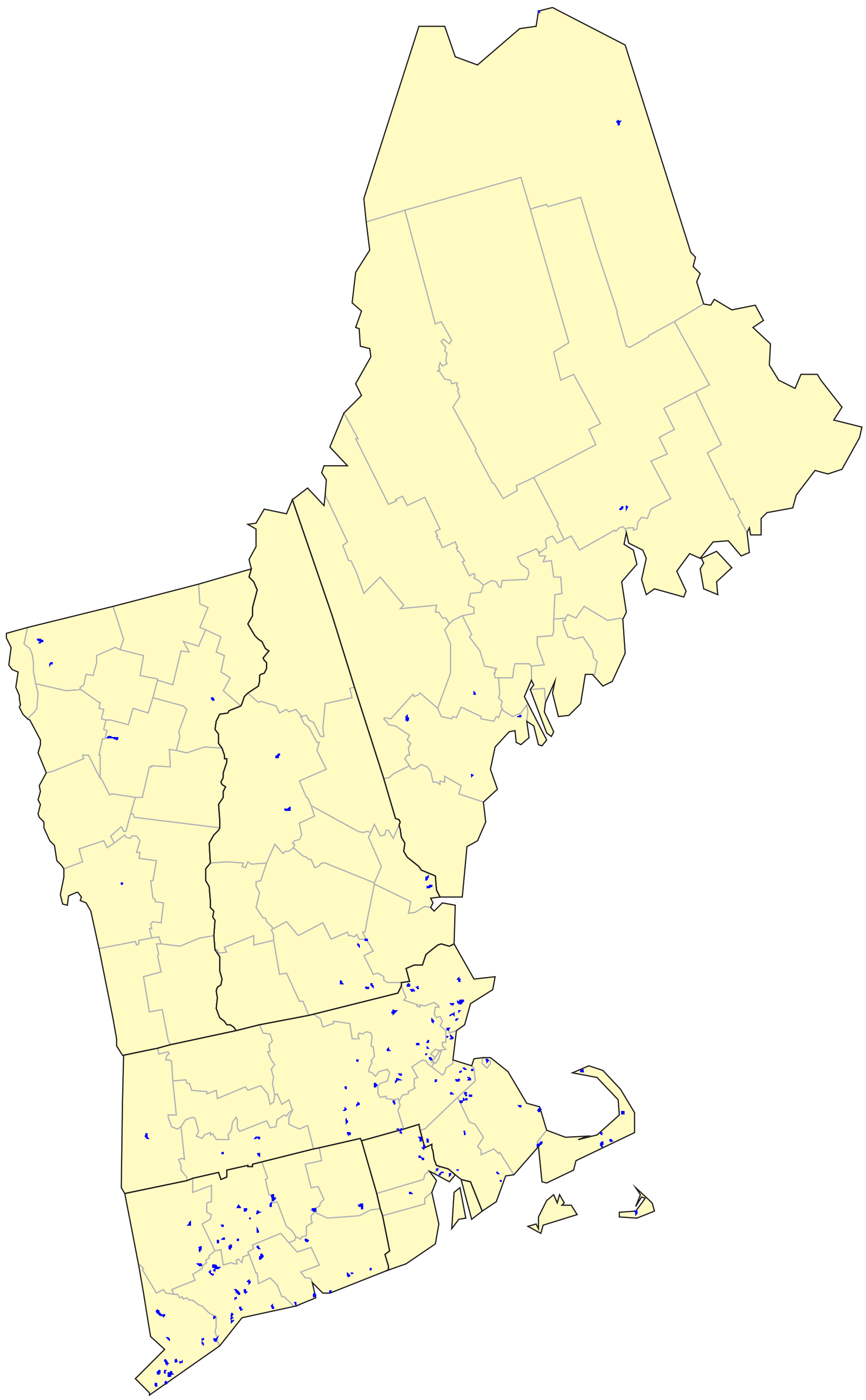


1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations



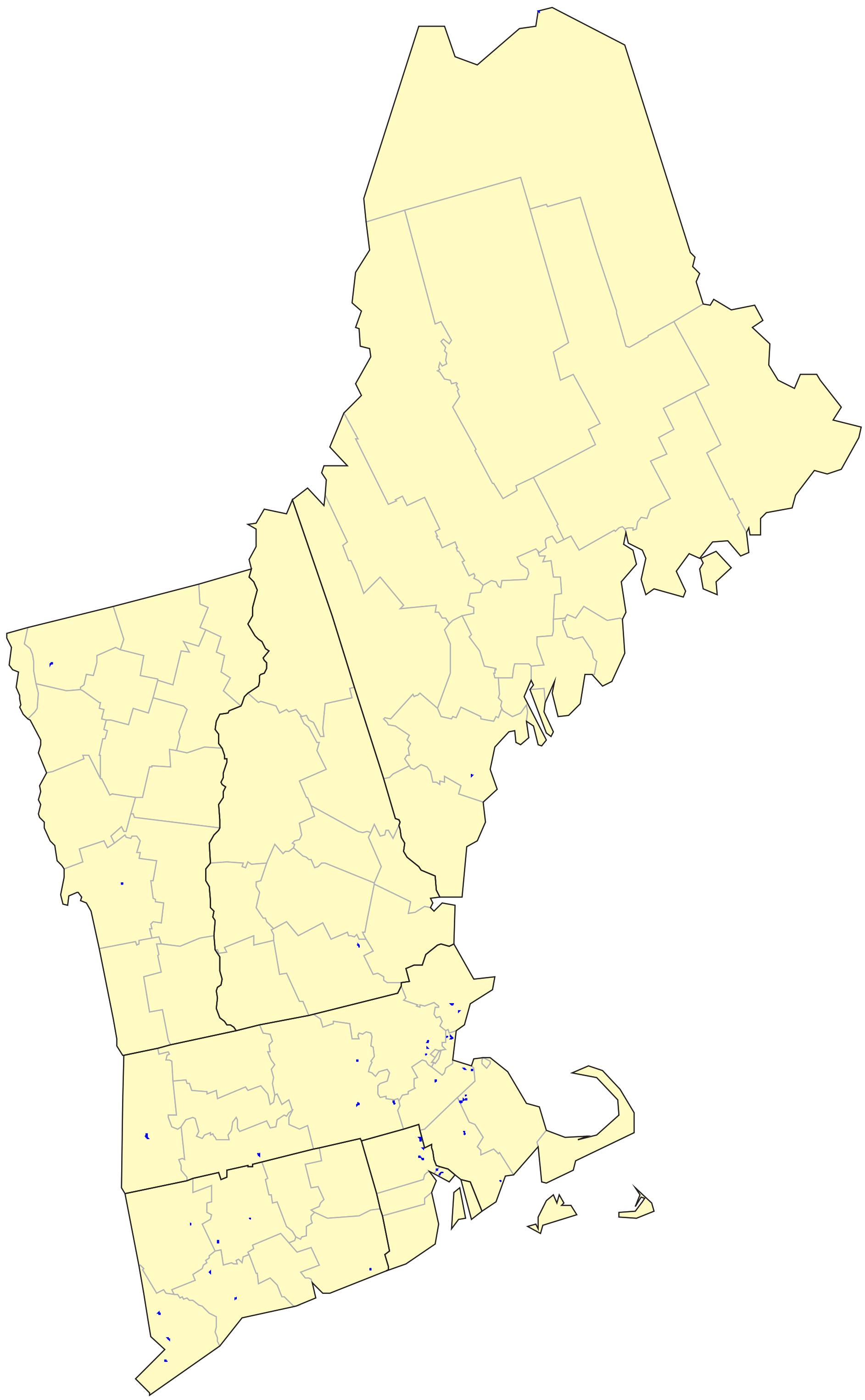
USEPA Region 1: Upper 30%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



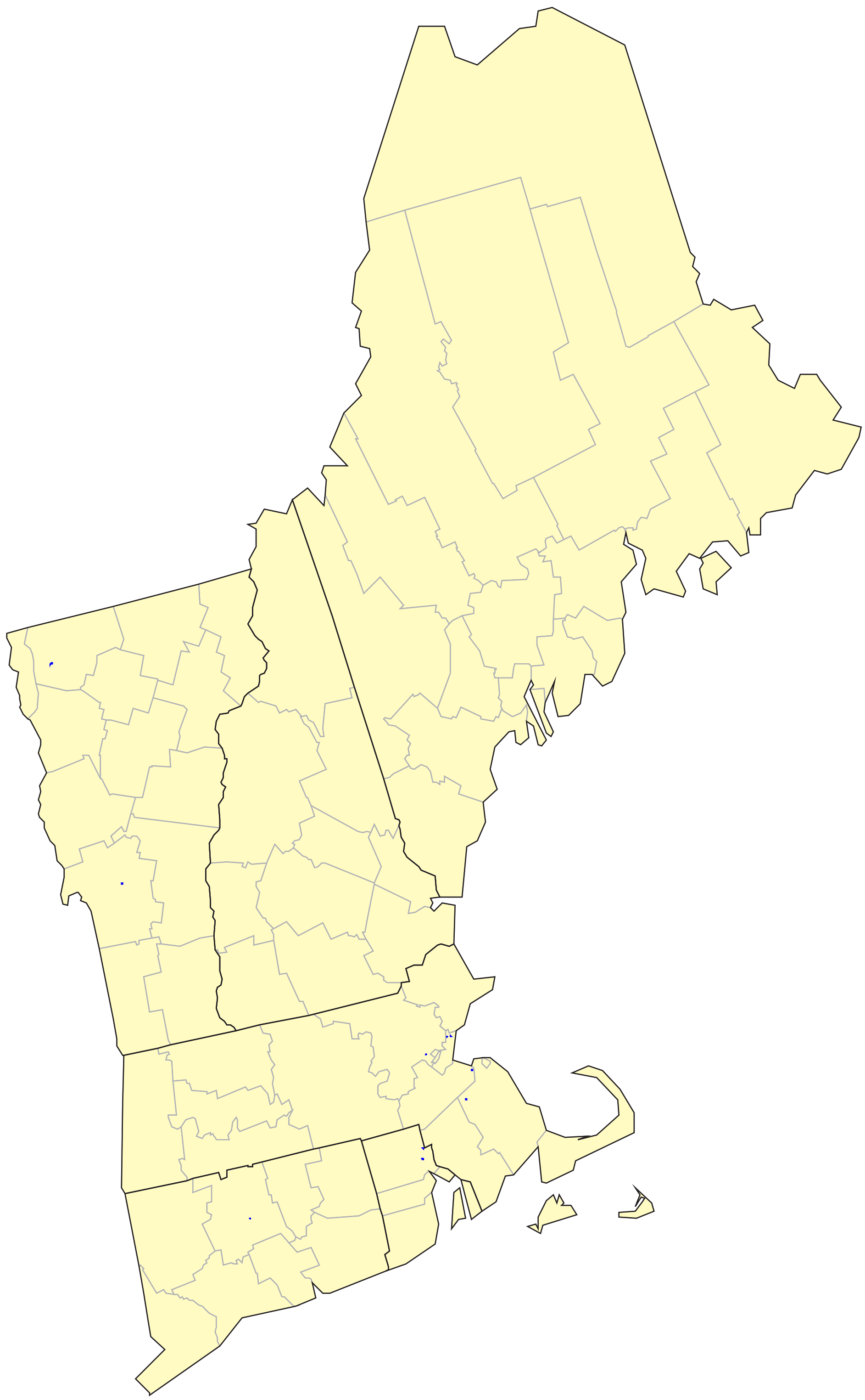
USEPA Region 1: Upper 10%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)

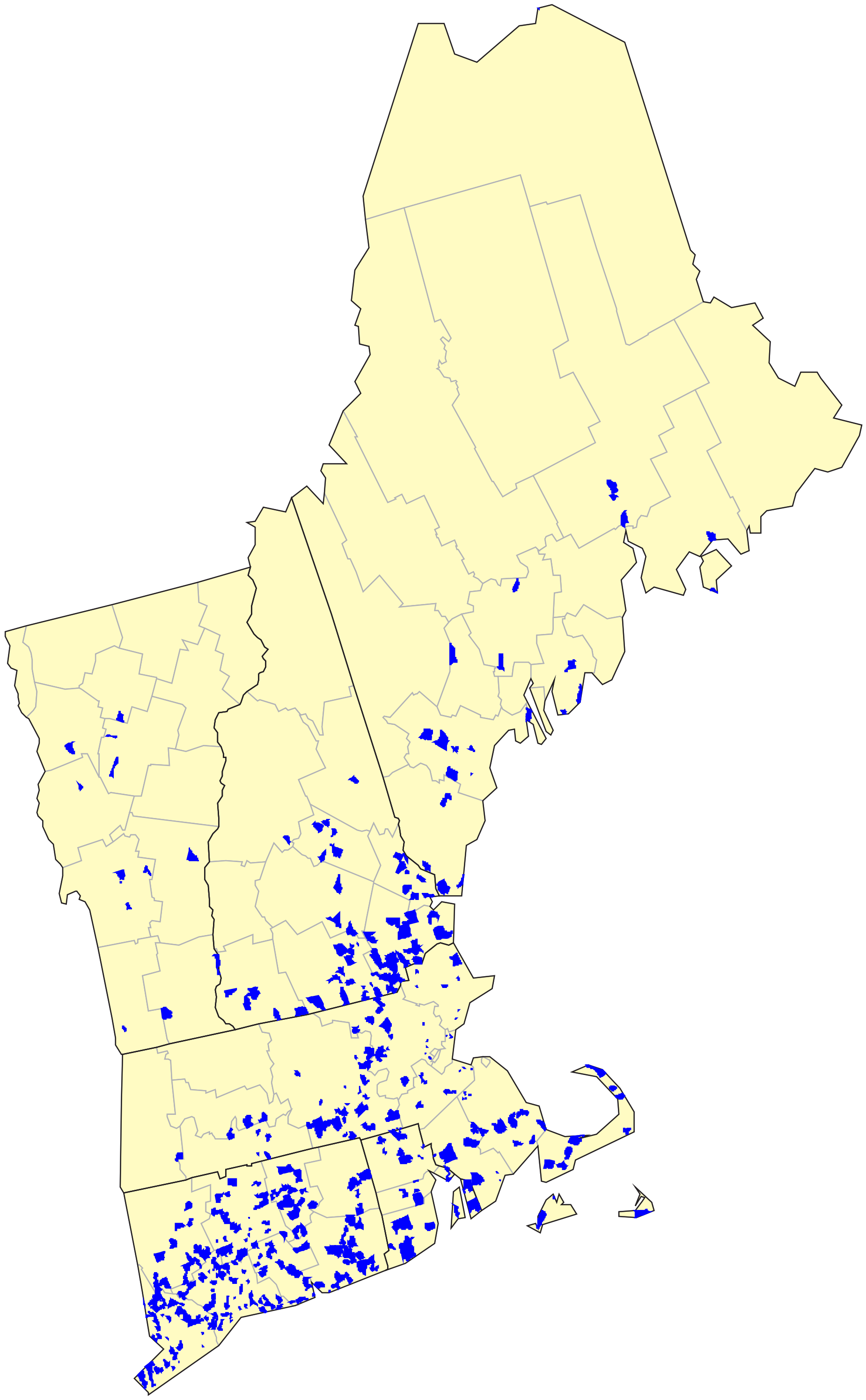


USEPA Region 1: Upper 3%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)

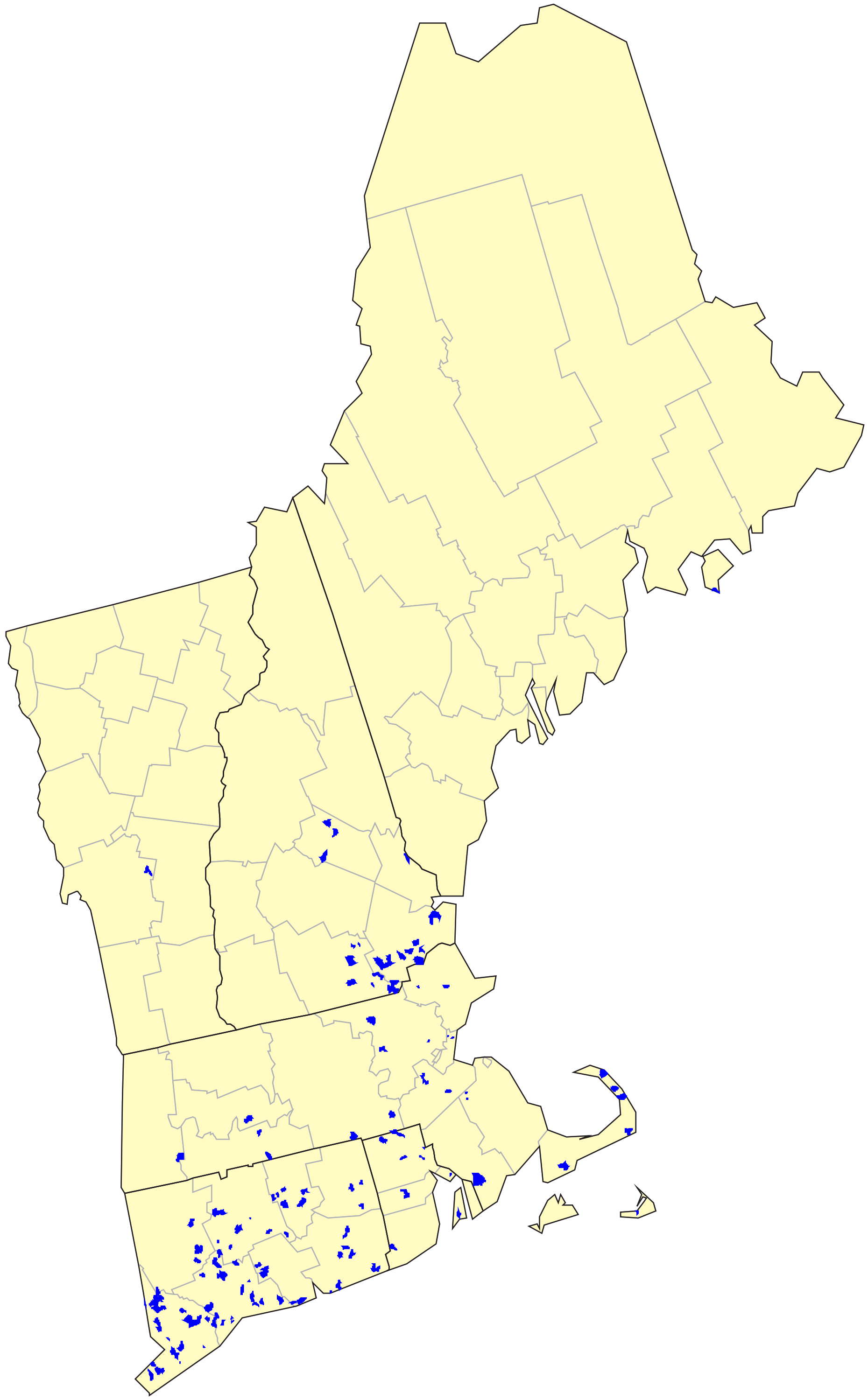


Vulnerability Index 1: Density of Service Stations
(stations per square mile)



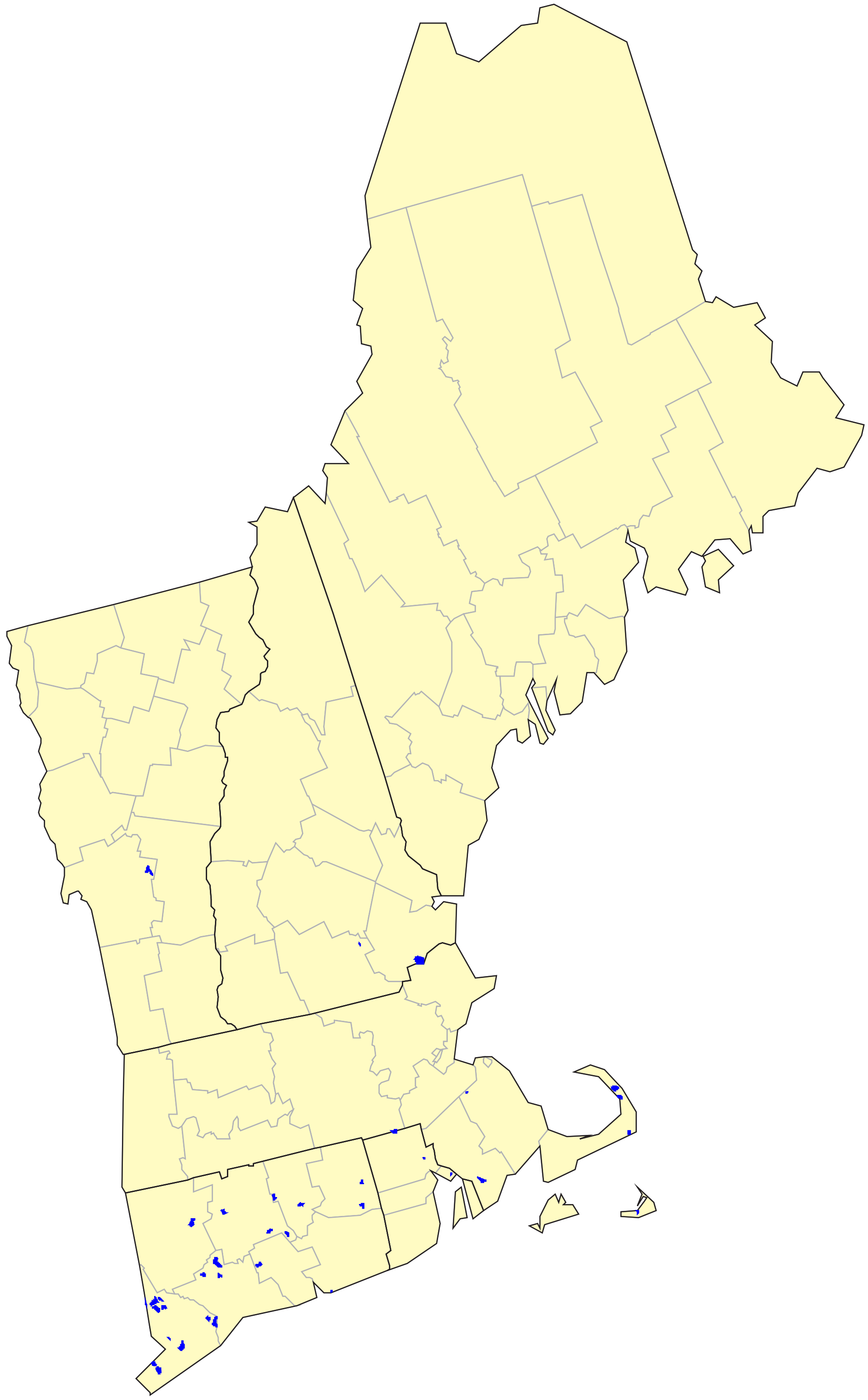
USEPA Region 1: Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



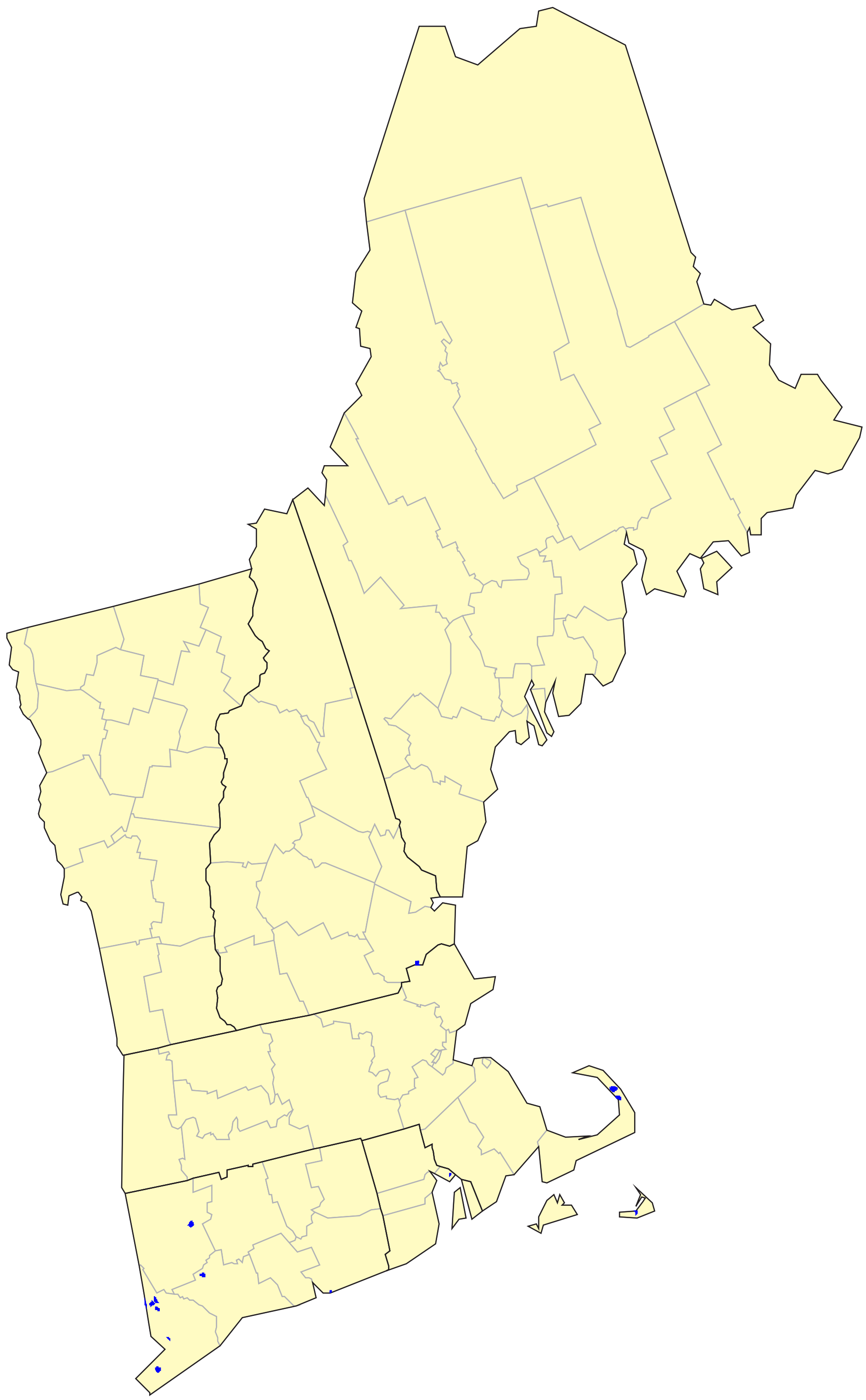
USEPA Region 1: Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



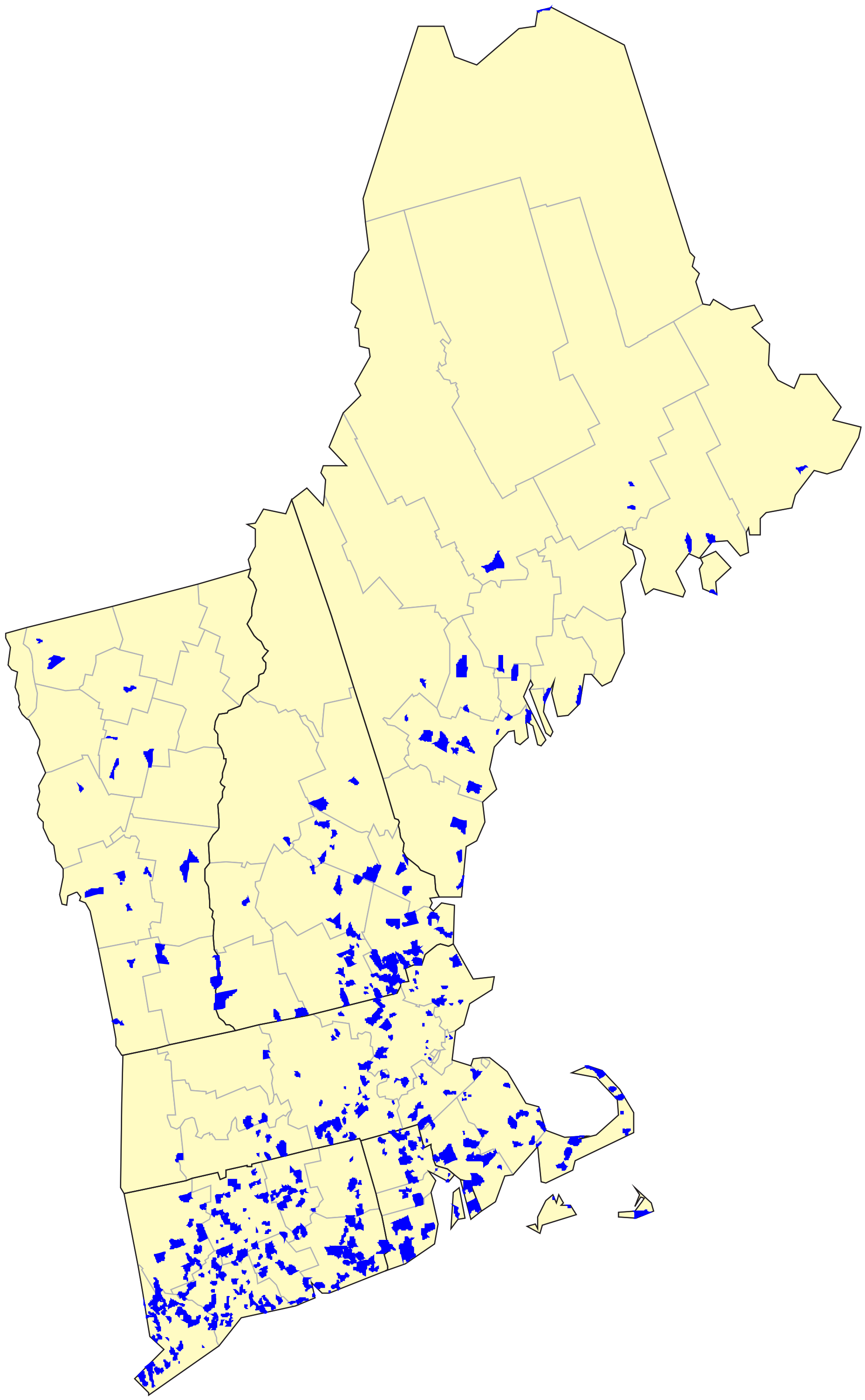
USEPA Region 1: Upper 3%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

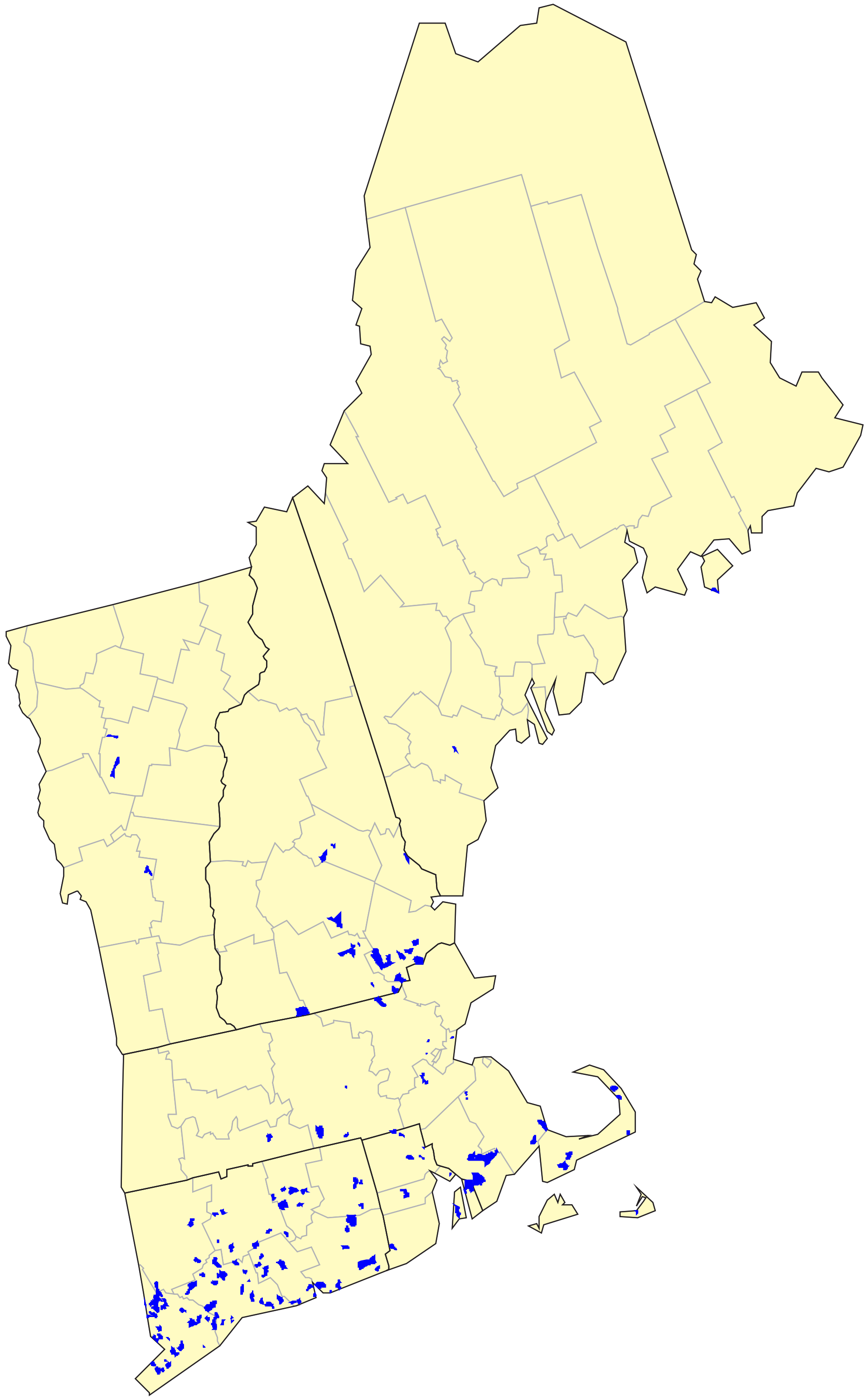


USEPA Region 1: Upper 1%

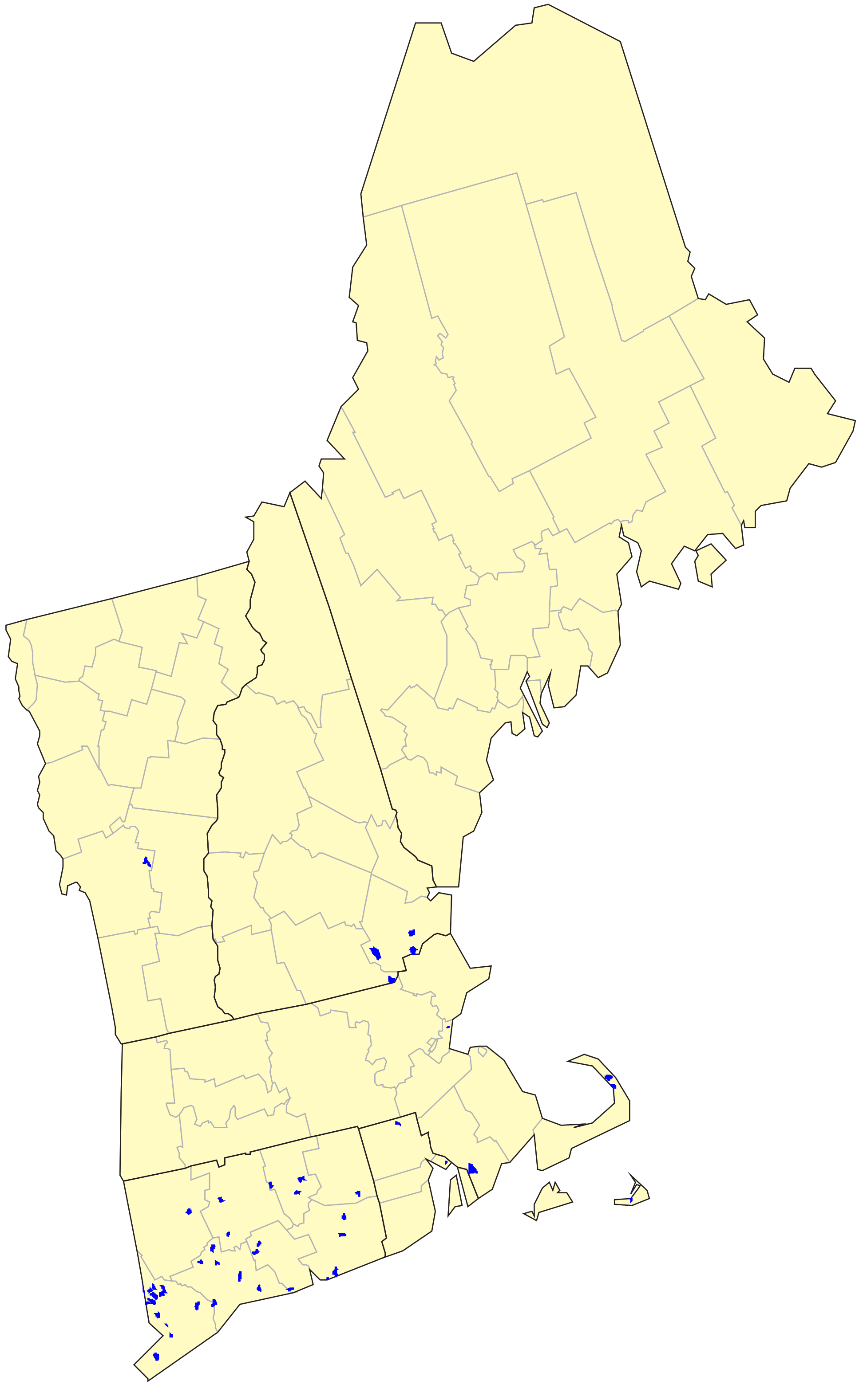
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



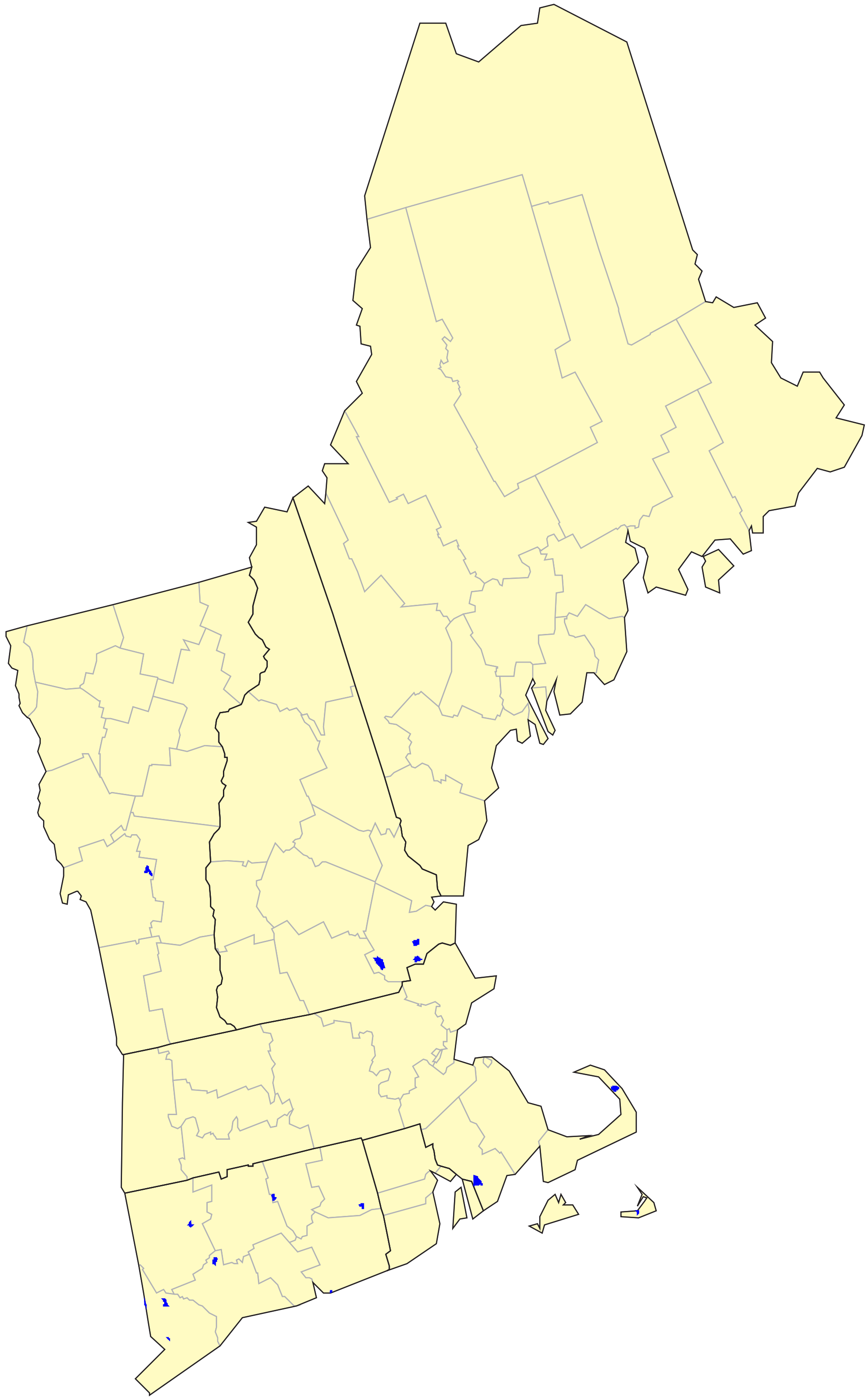
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 1: Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 1: Upper 10%



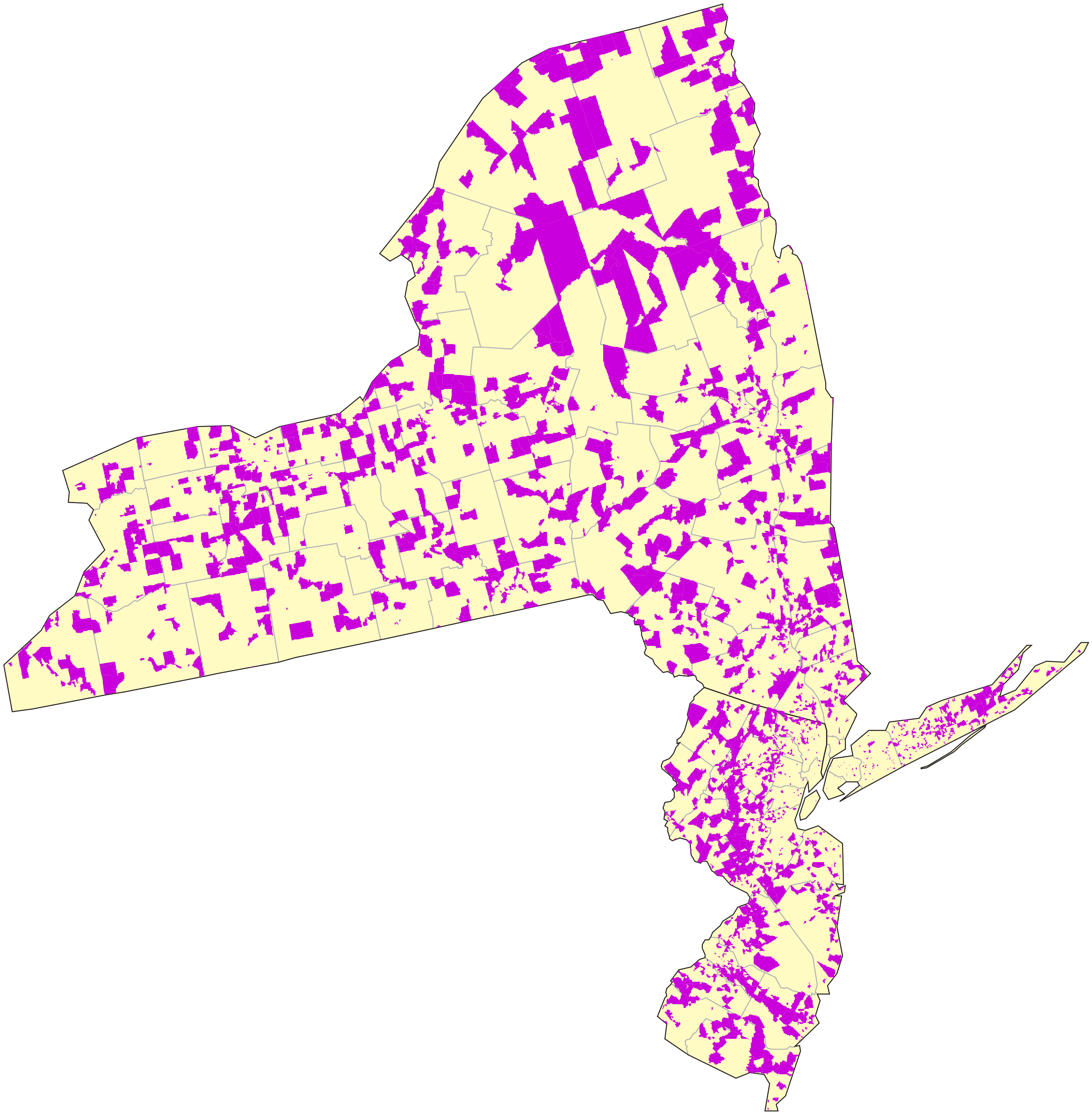
Vulnerability Index 3: $\dfrac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 1: Upper 3%



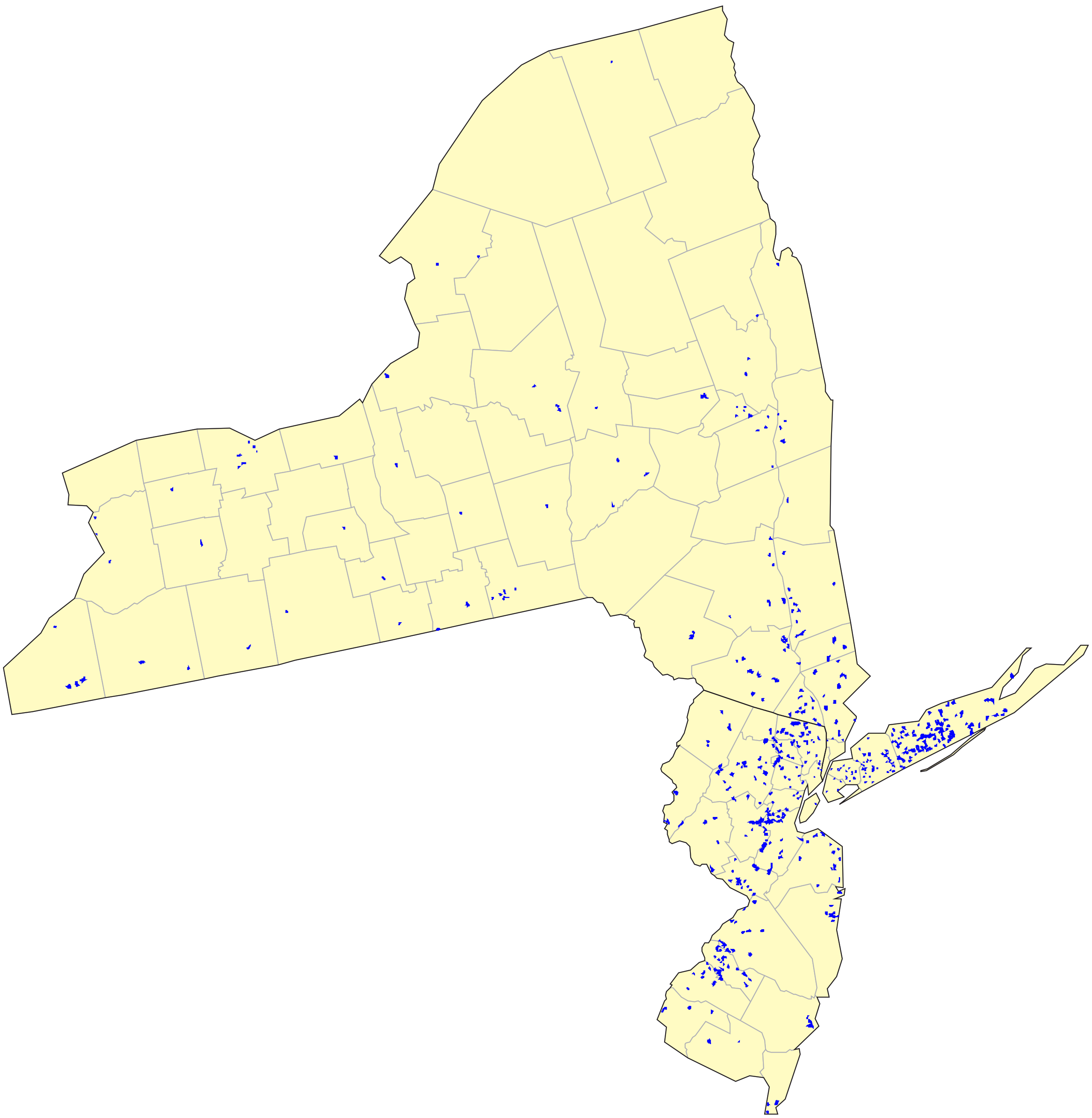
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 1: Upper 1%

Appendix C

USEPA Region 2 Vulnerability

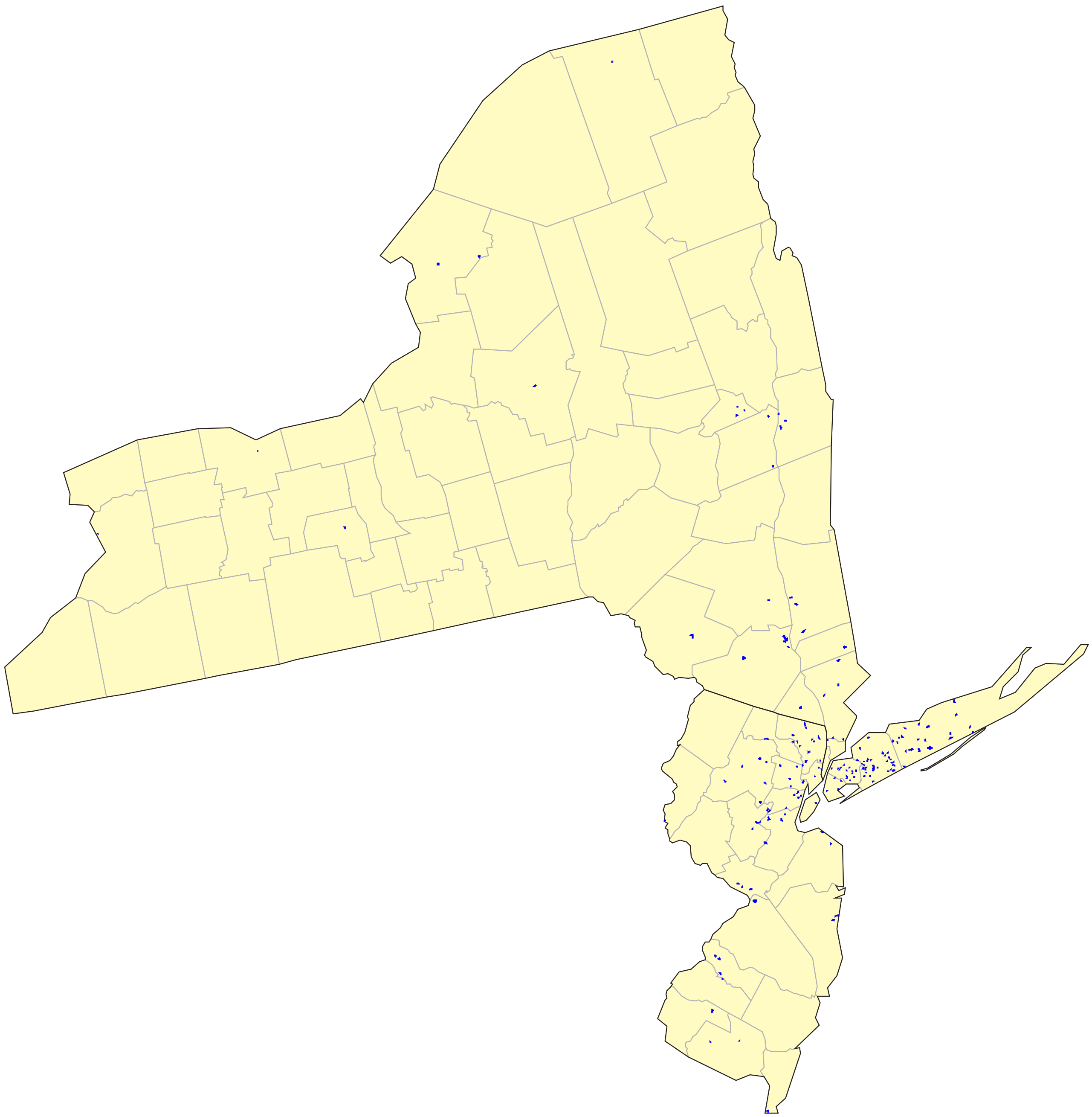


1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations



USEPA Region 2: Upper 30%

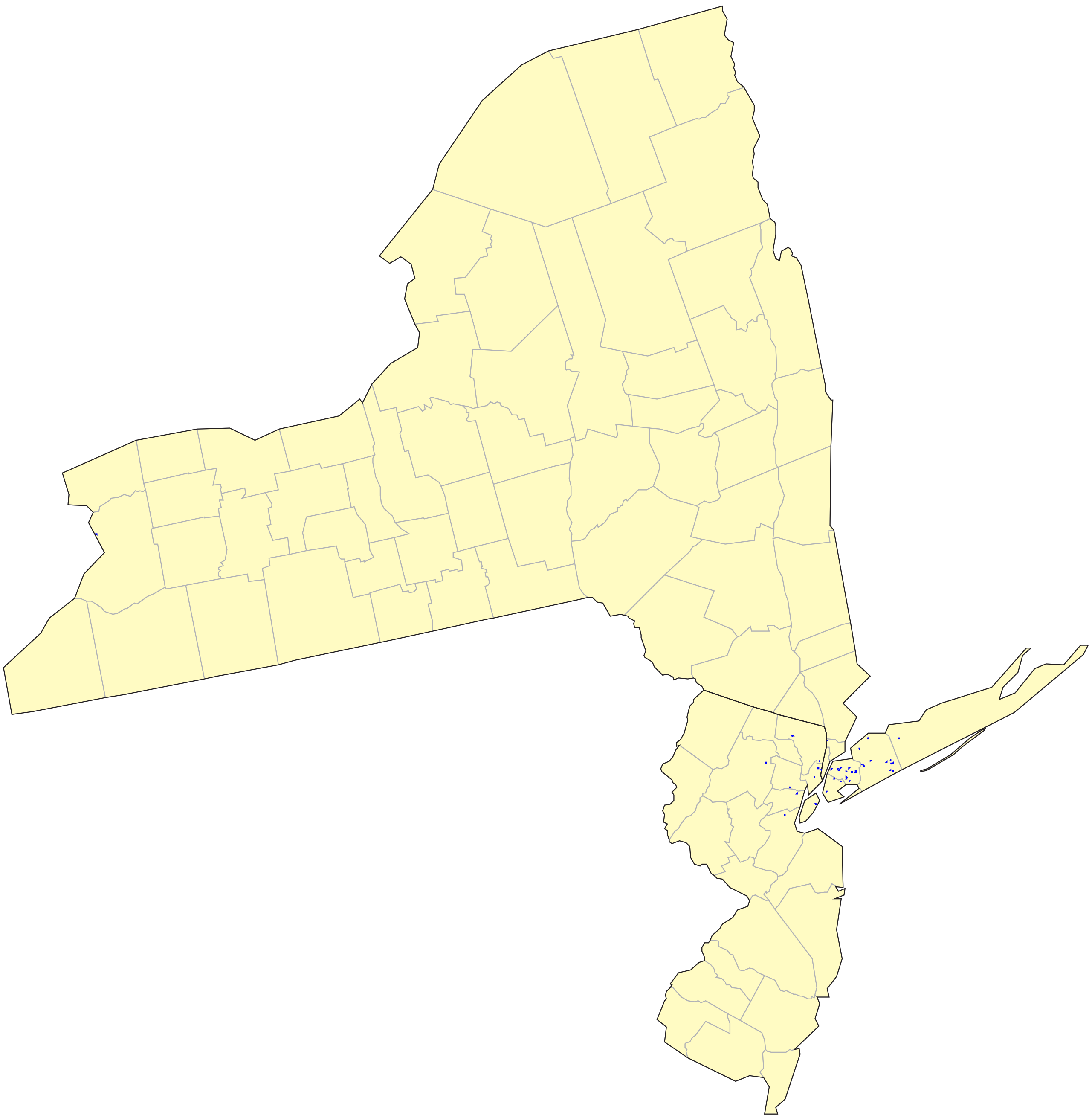
Vulnerability Index 1: Density of Service Stations
(stations per square mile)



USEPA Region 2: Upper 10%

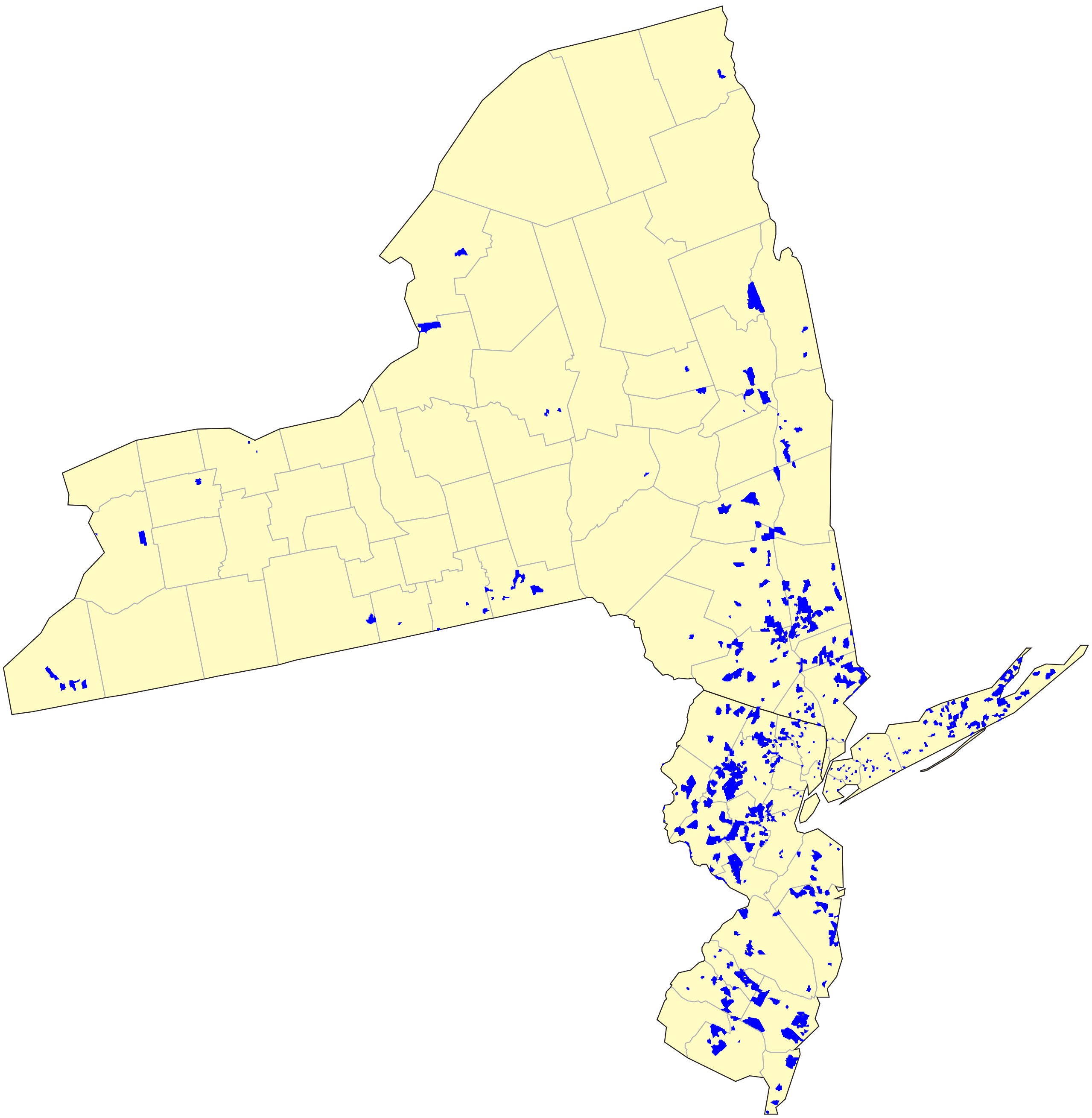
Vulnerability Index 1: Density of Service Stations

(stations per square mile)



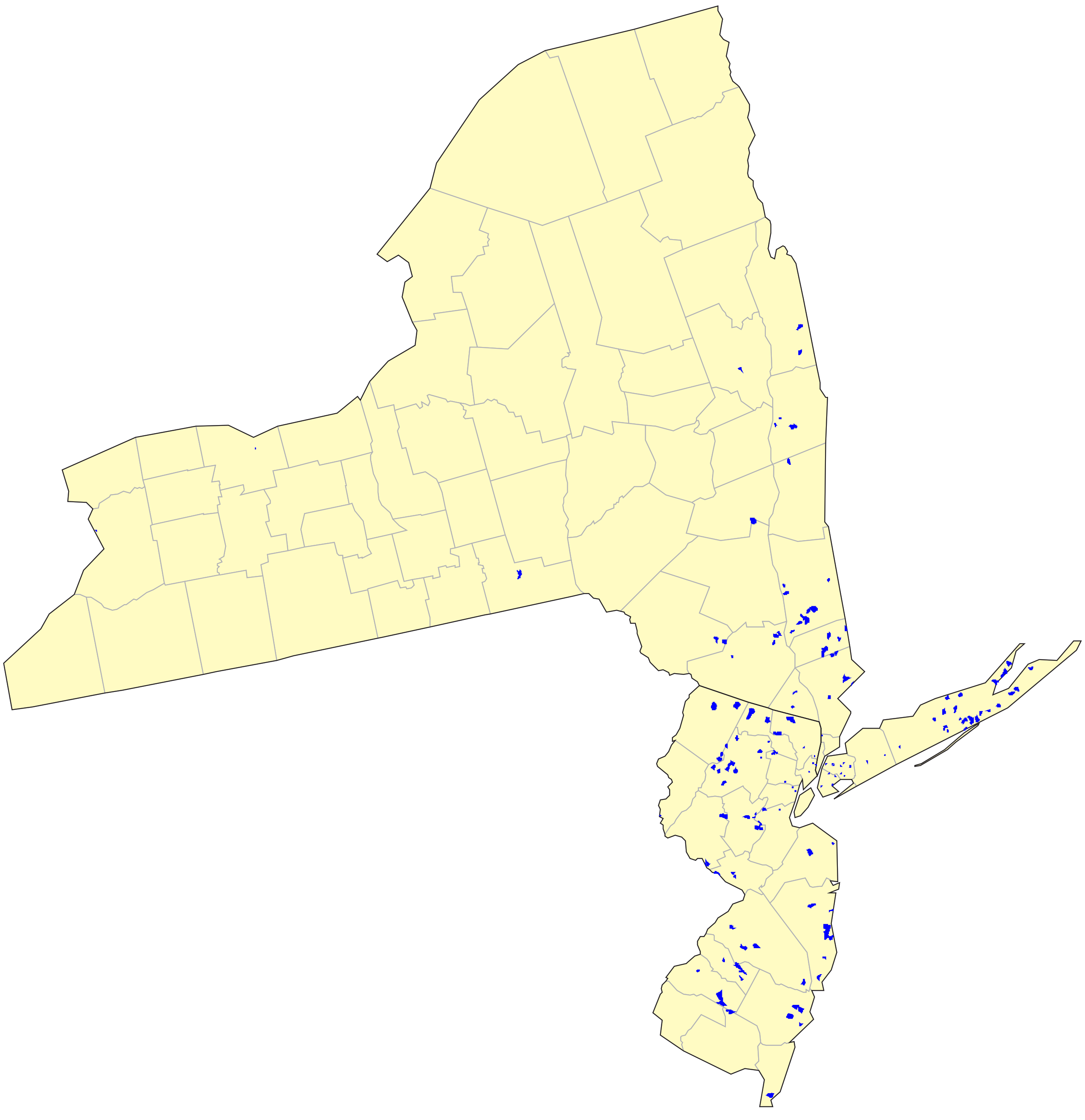
USEPA Region 2: Upper 3%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



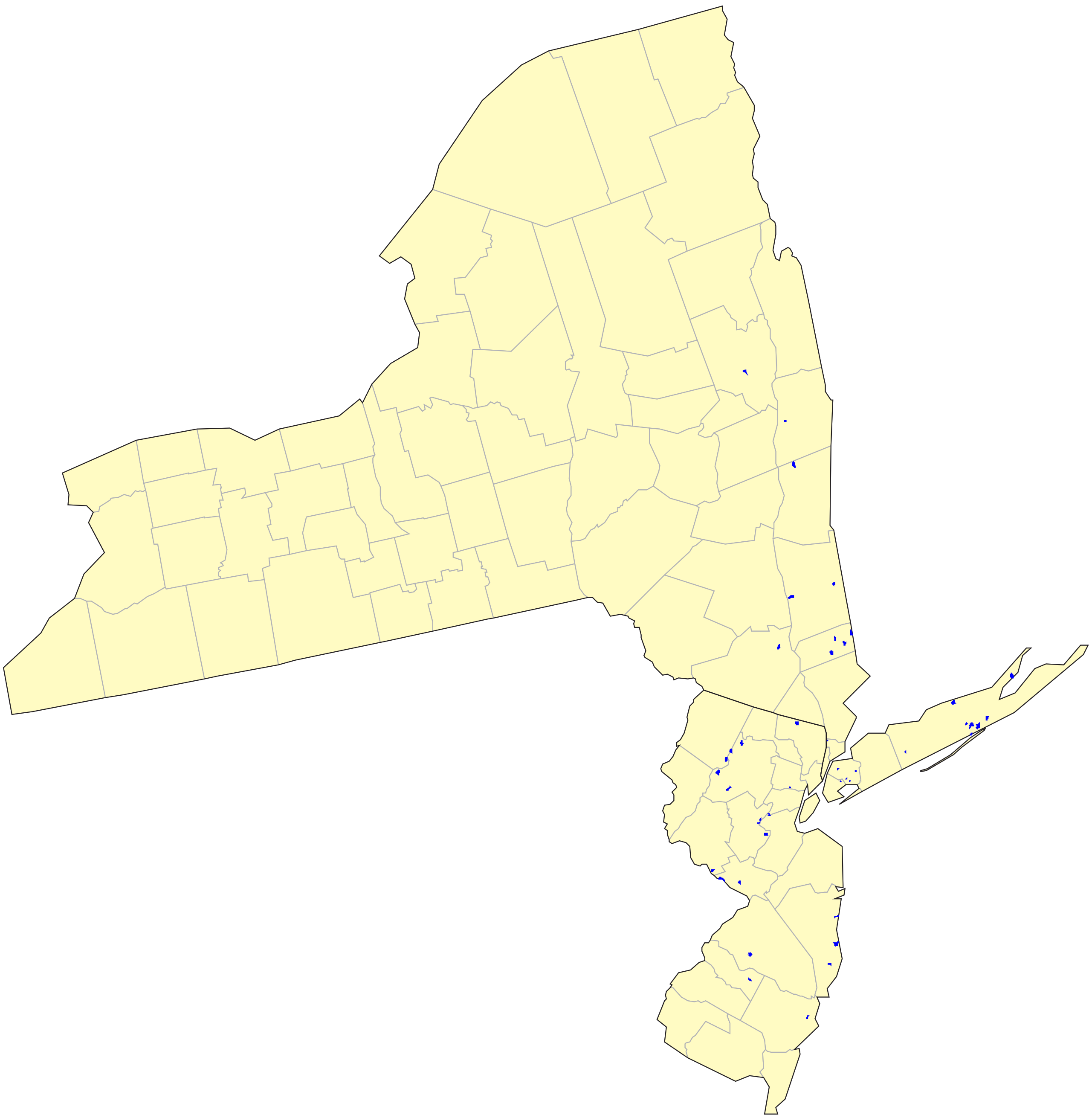
USEPA Region 2: Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



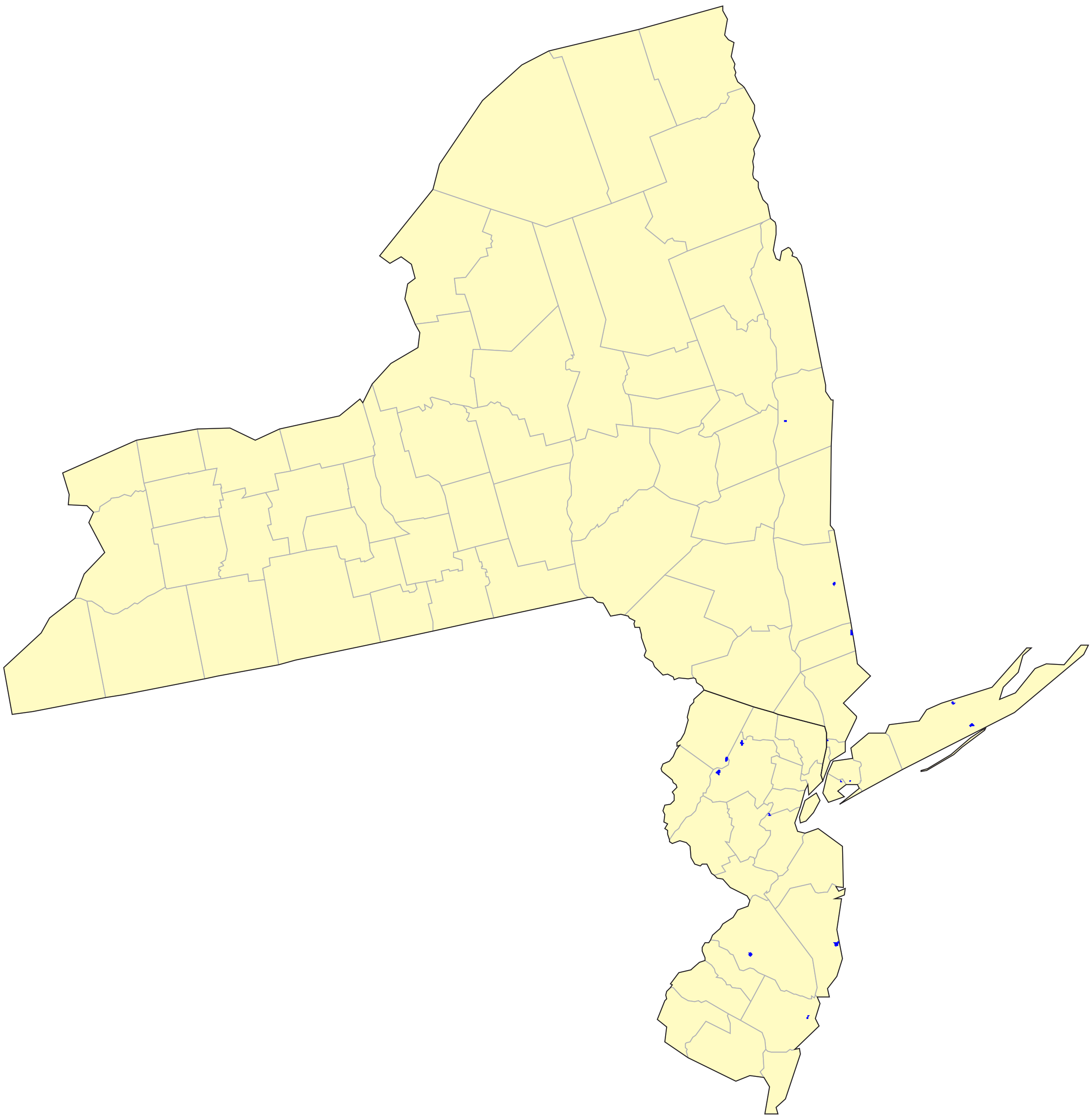
USEPA Region 2: Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



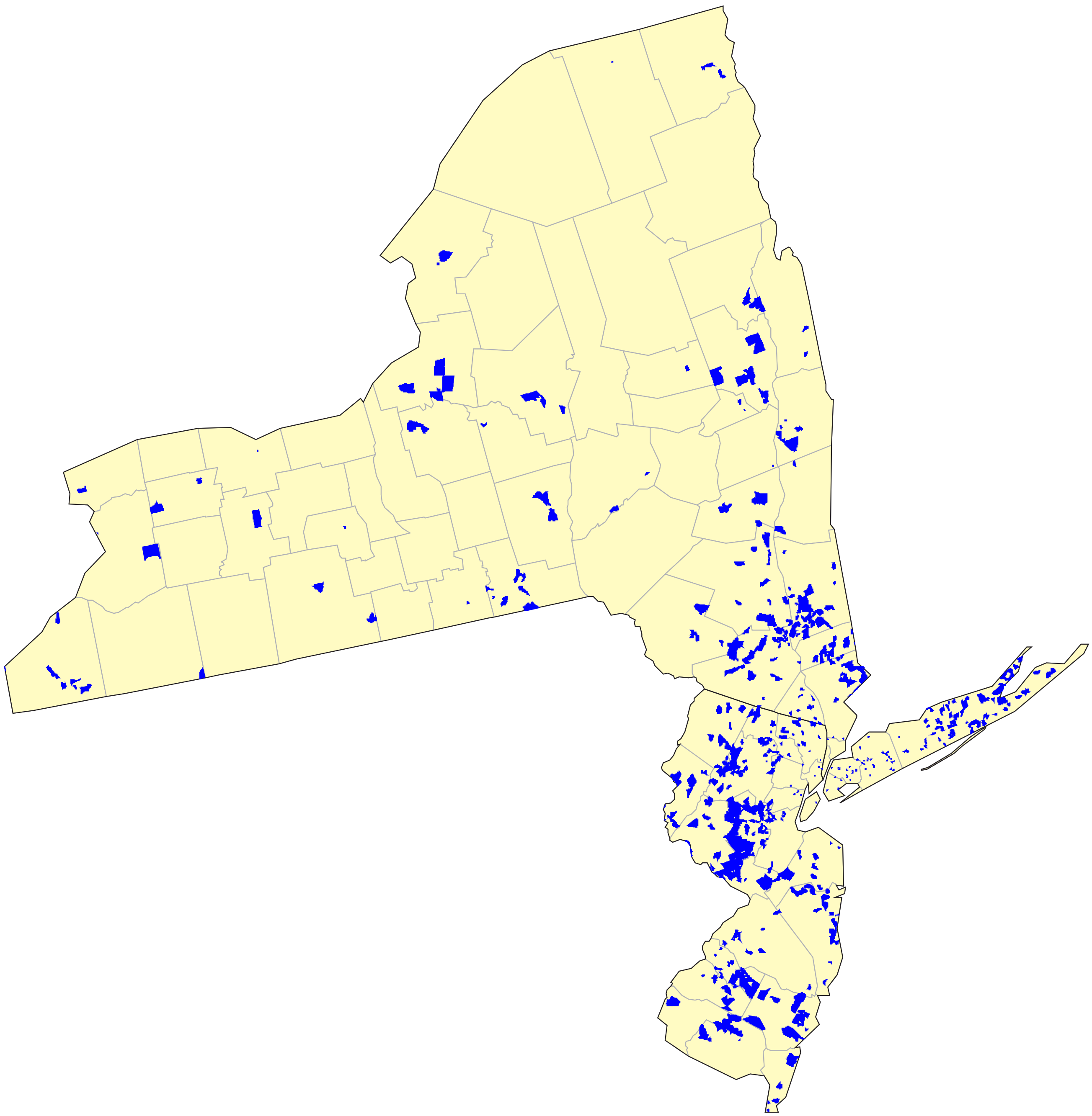
USEPA Region 2: Upper 3%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

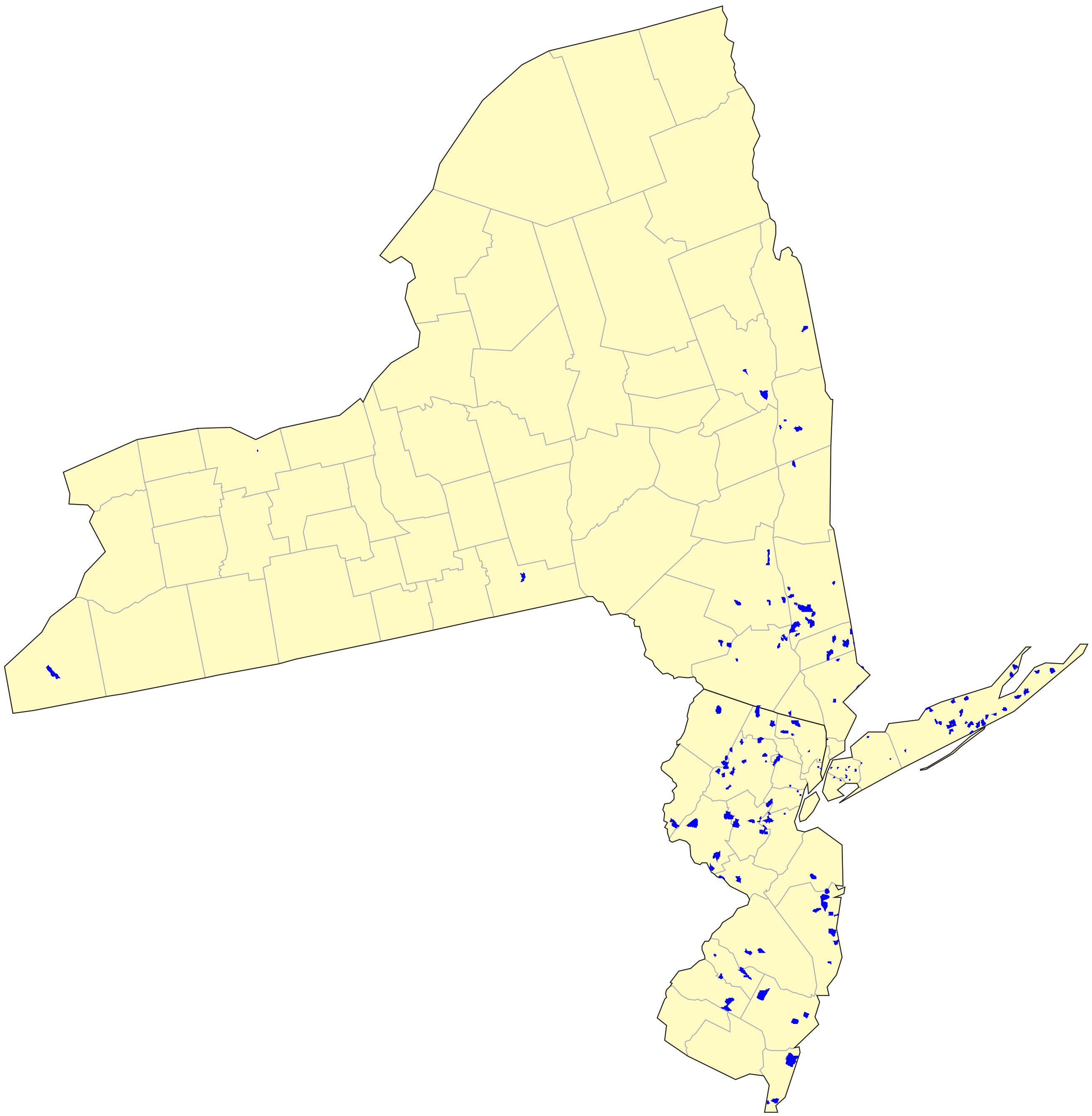


USEPA Region 2: Upper 1%

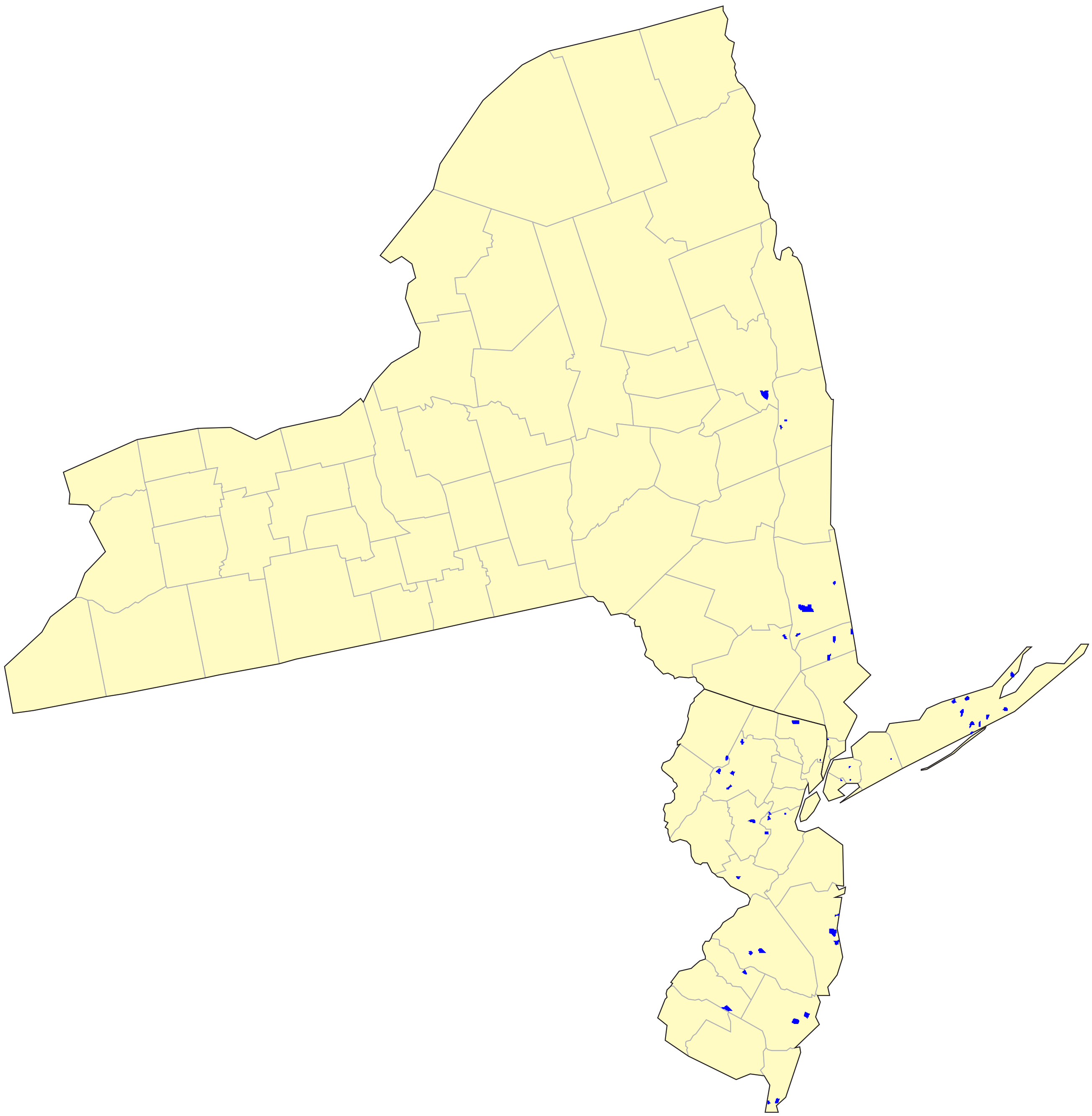
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



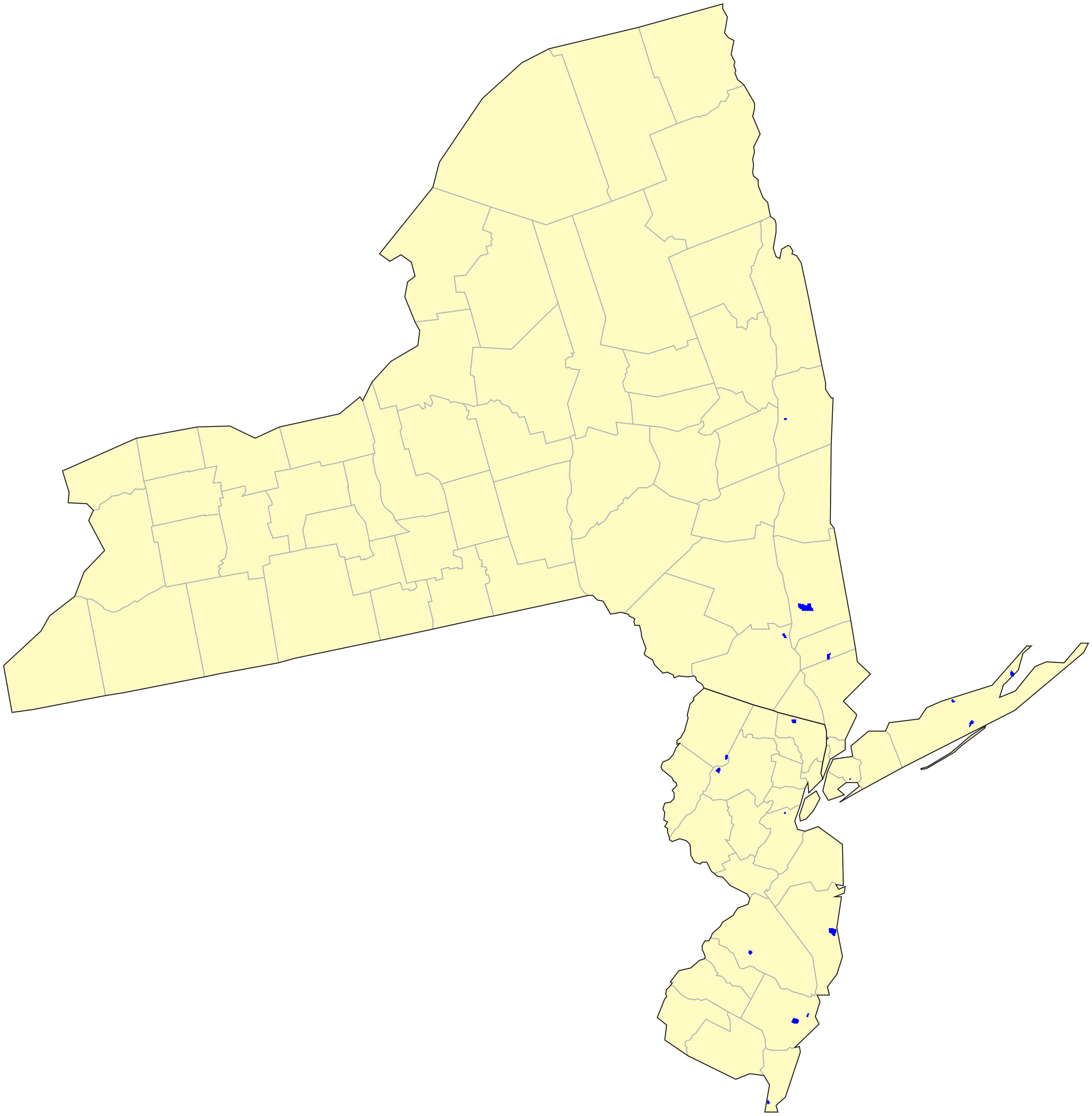
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 2: Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 2: Upper 10%



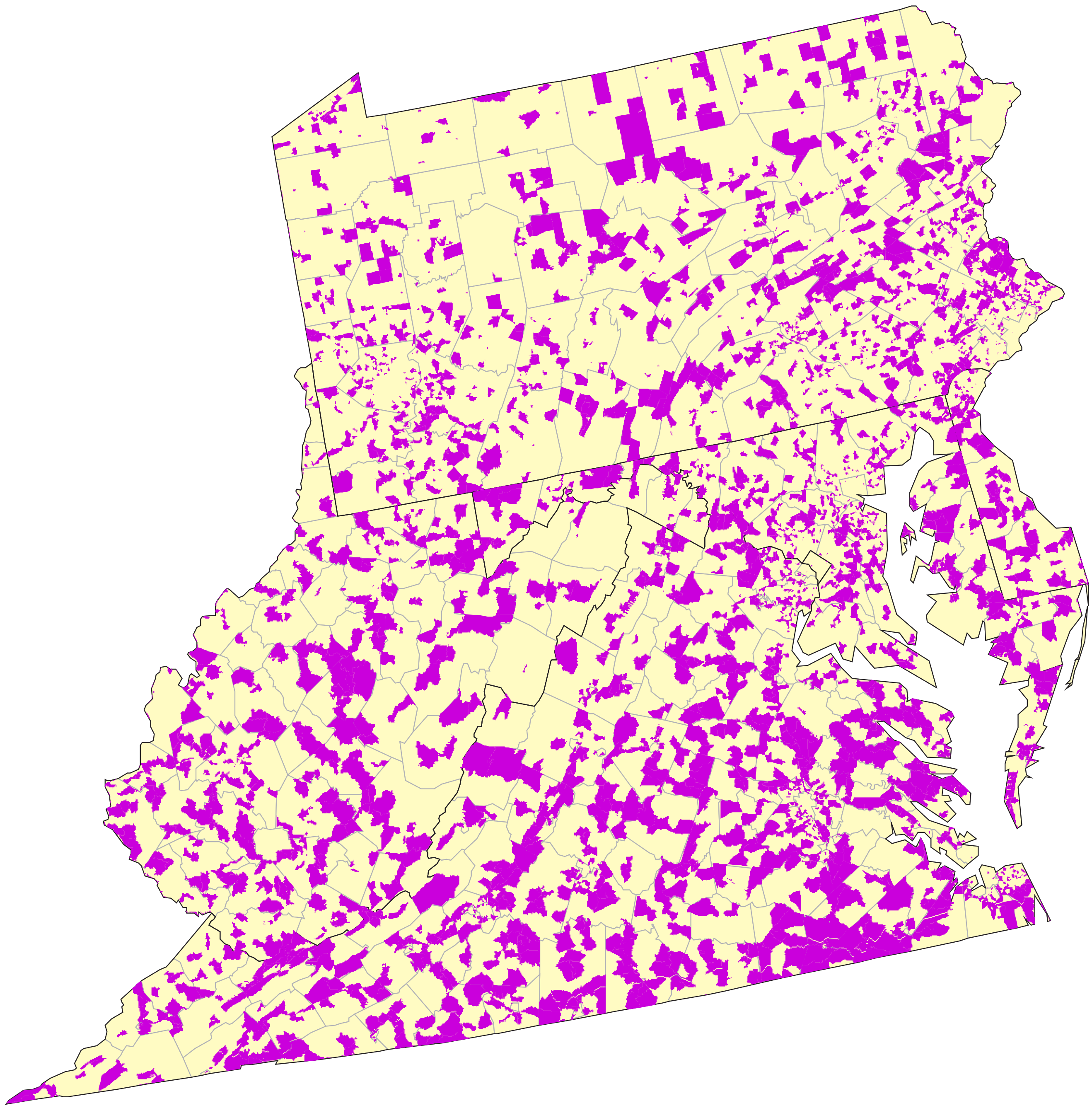
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 2: Upper 3%



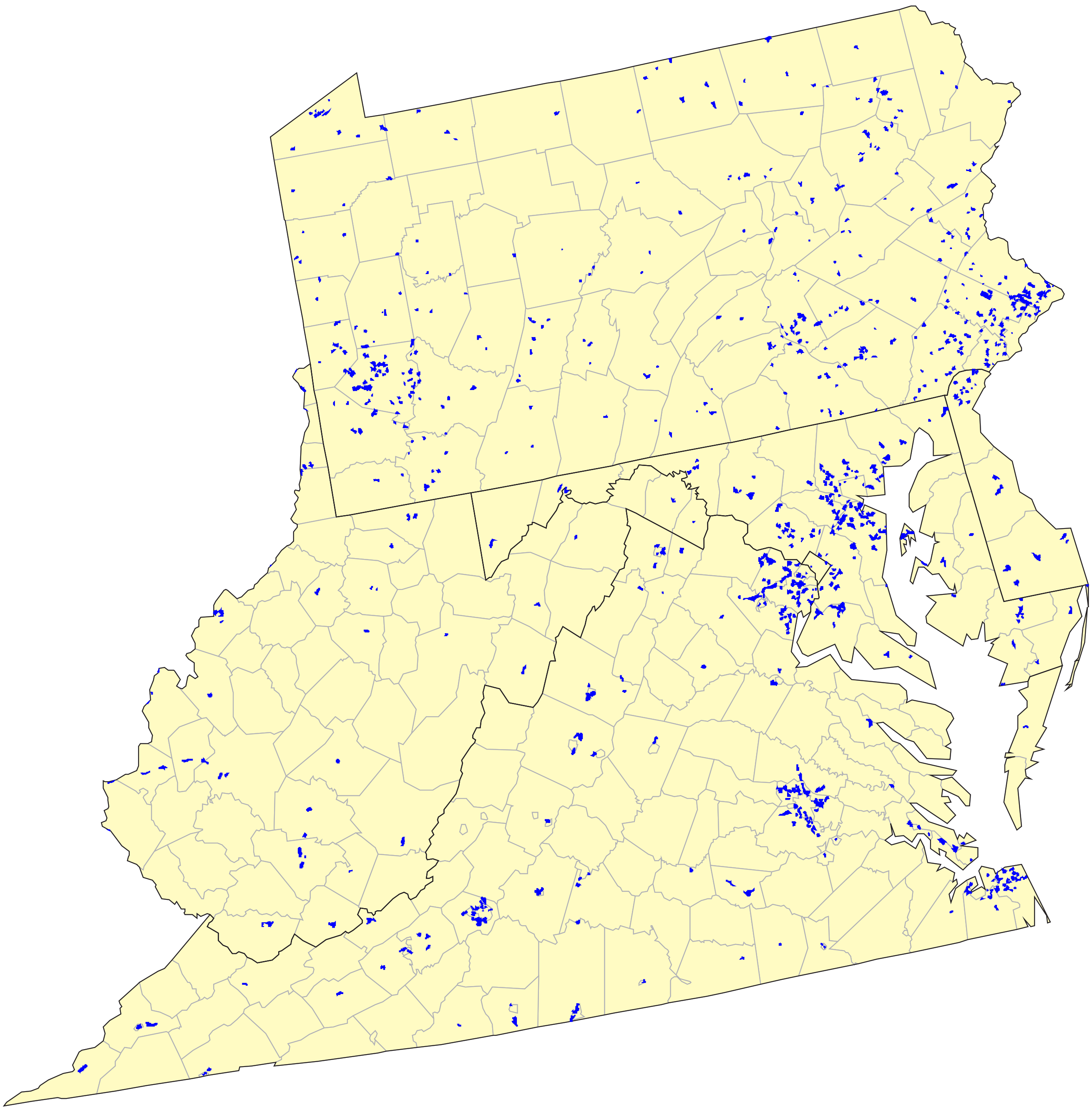
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 2: Upper 1%

Appendix D

USEPA Region 3 Vulnerability

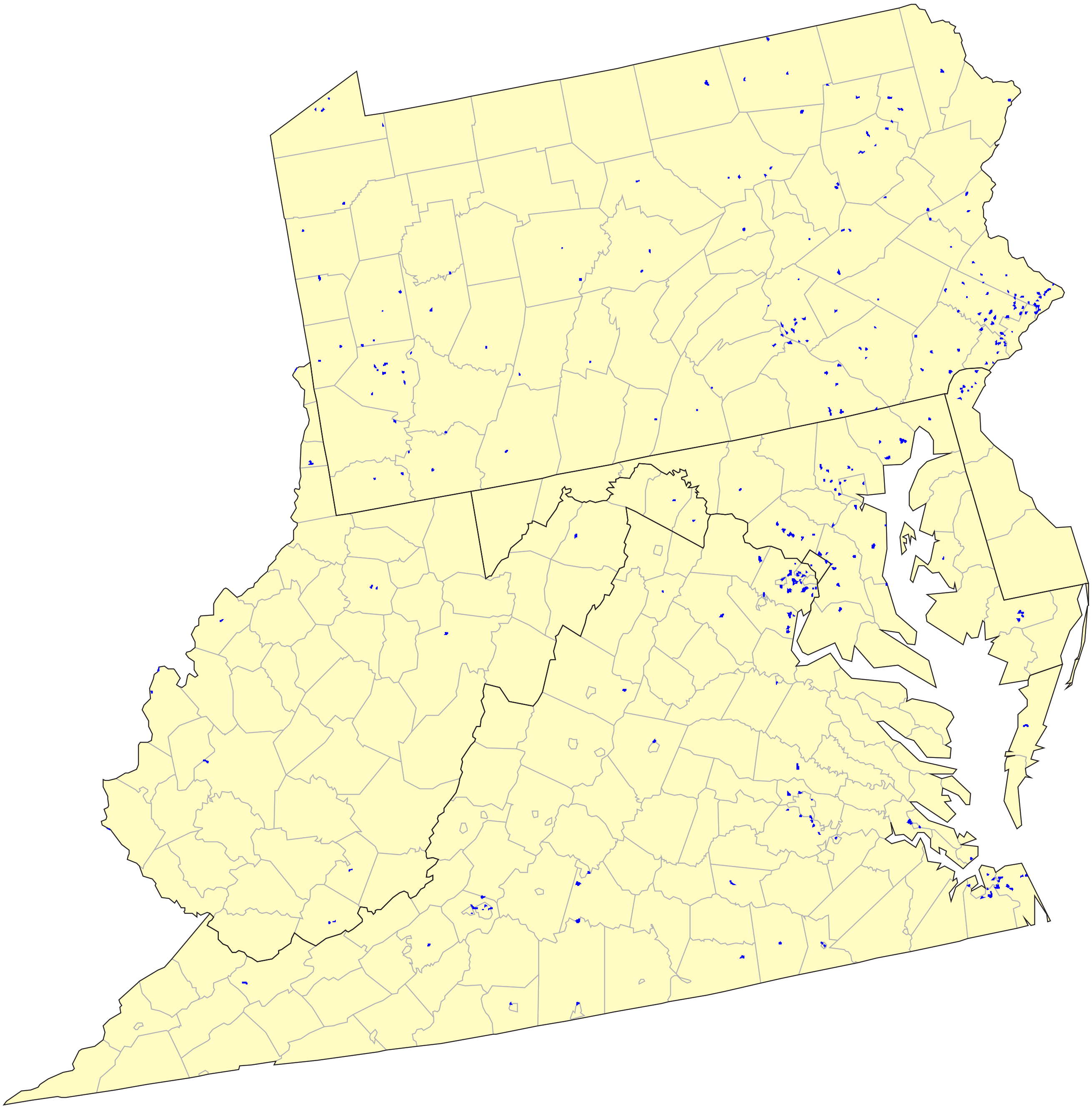


1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations



USEPA Region 3: Upper 30%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



USEPA Region 3: Upper 10%

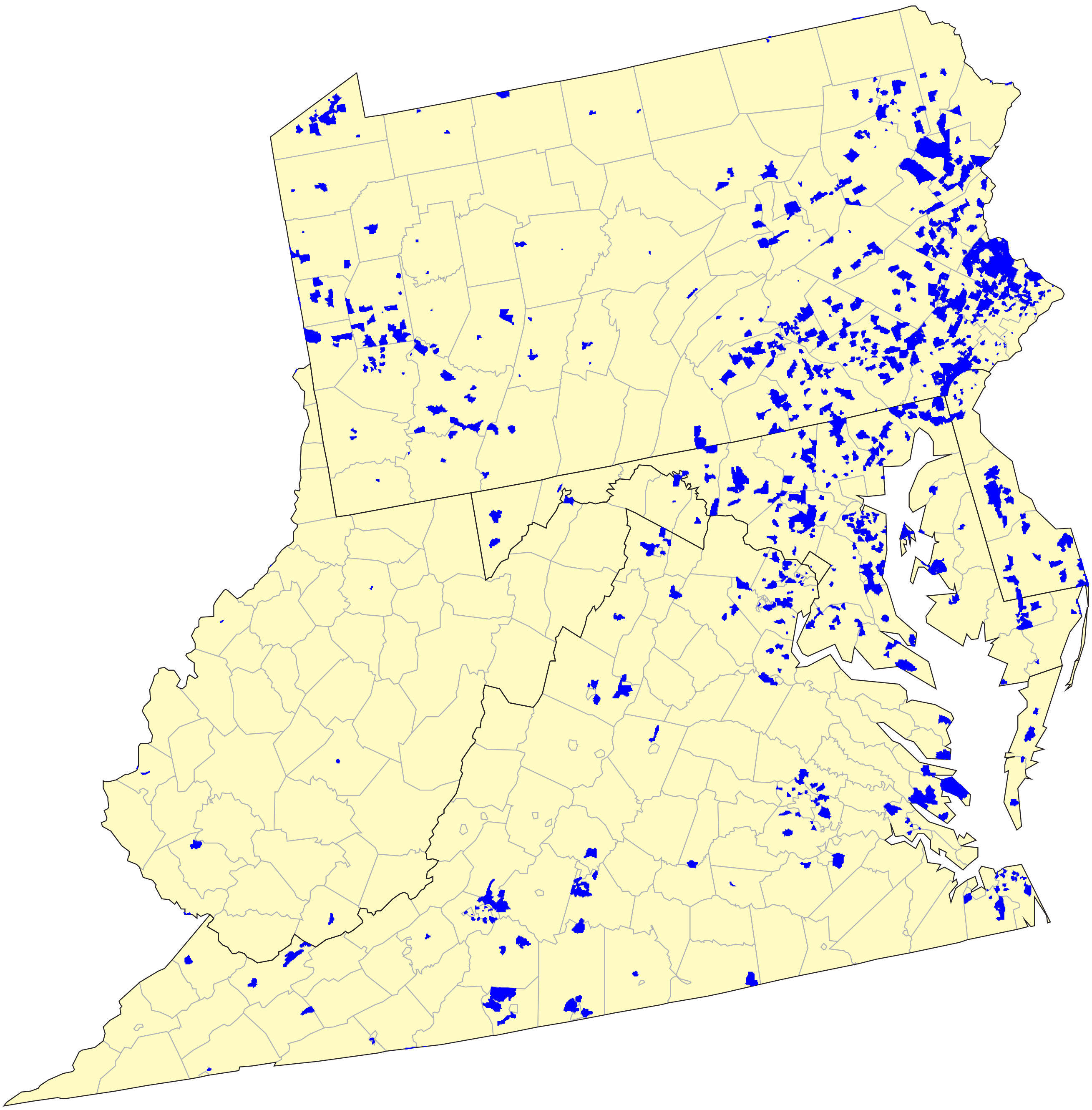
Vulnerability Index 1: Density of Service Stations
(stations per square mile)

USEPA Region 3: Upper 3%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)

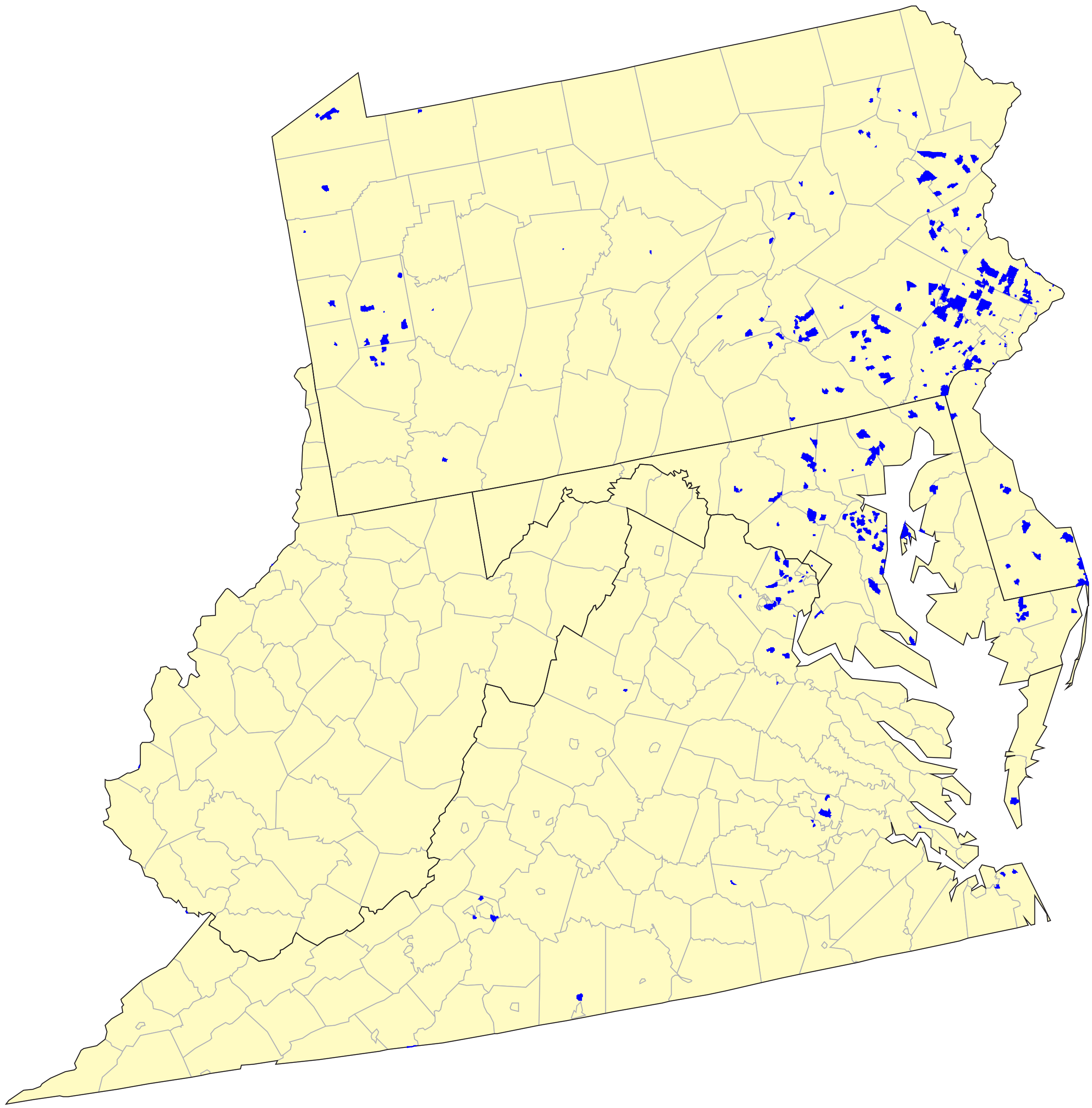
USEPA Region 3: Upper 1%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



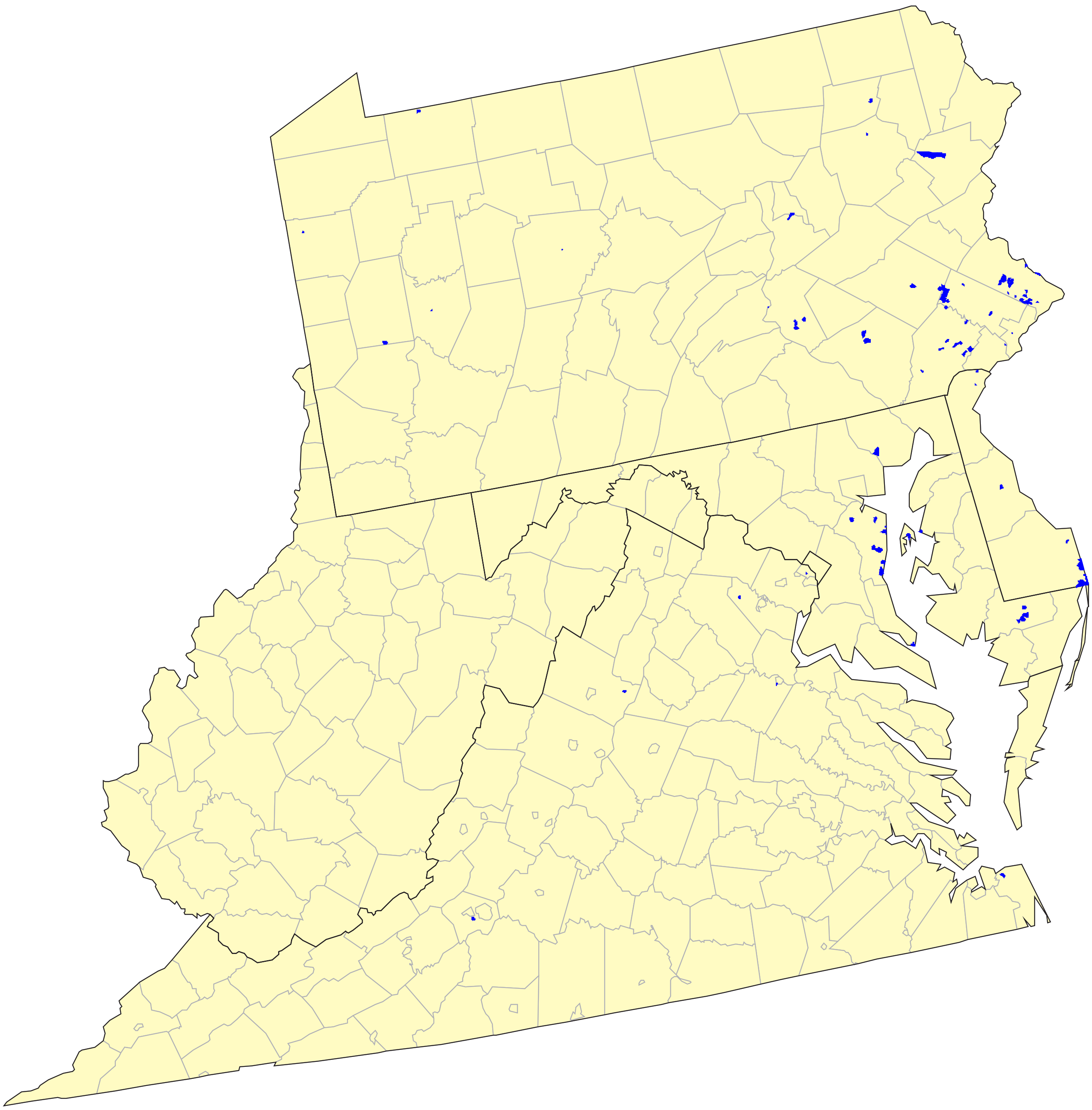
USEPA Region 3: Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



USEPA Region 3: Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

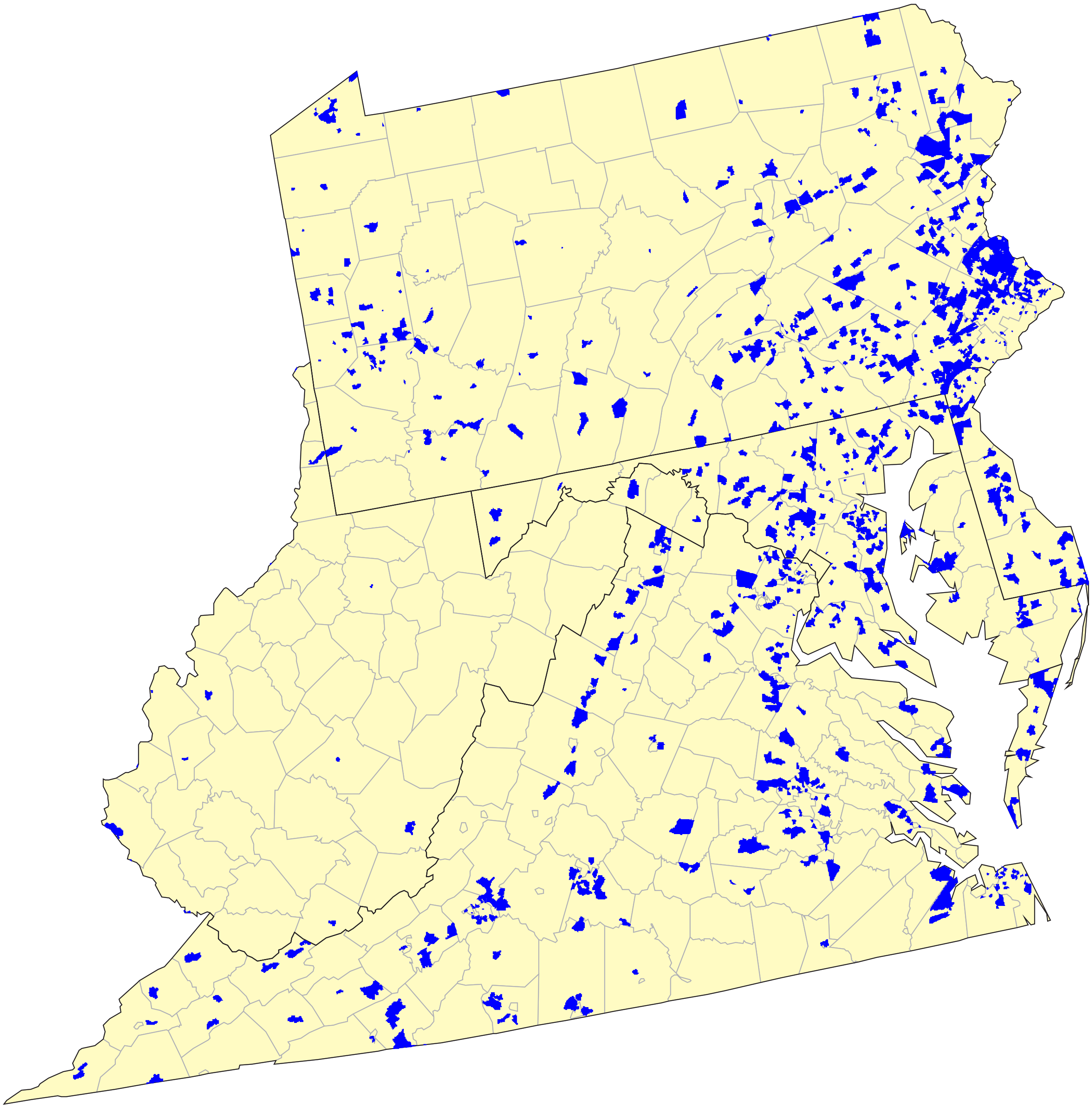


USEPA Region 3: Upper 3%

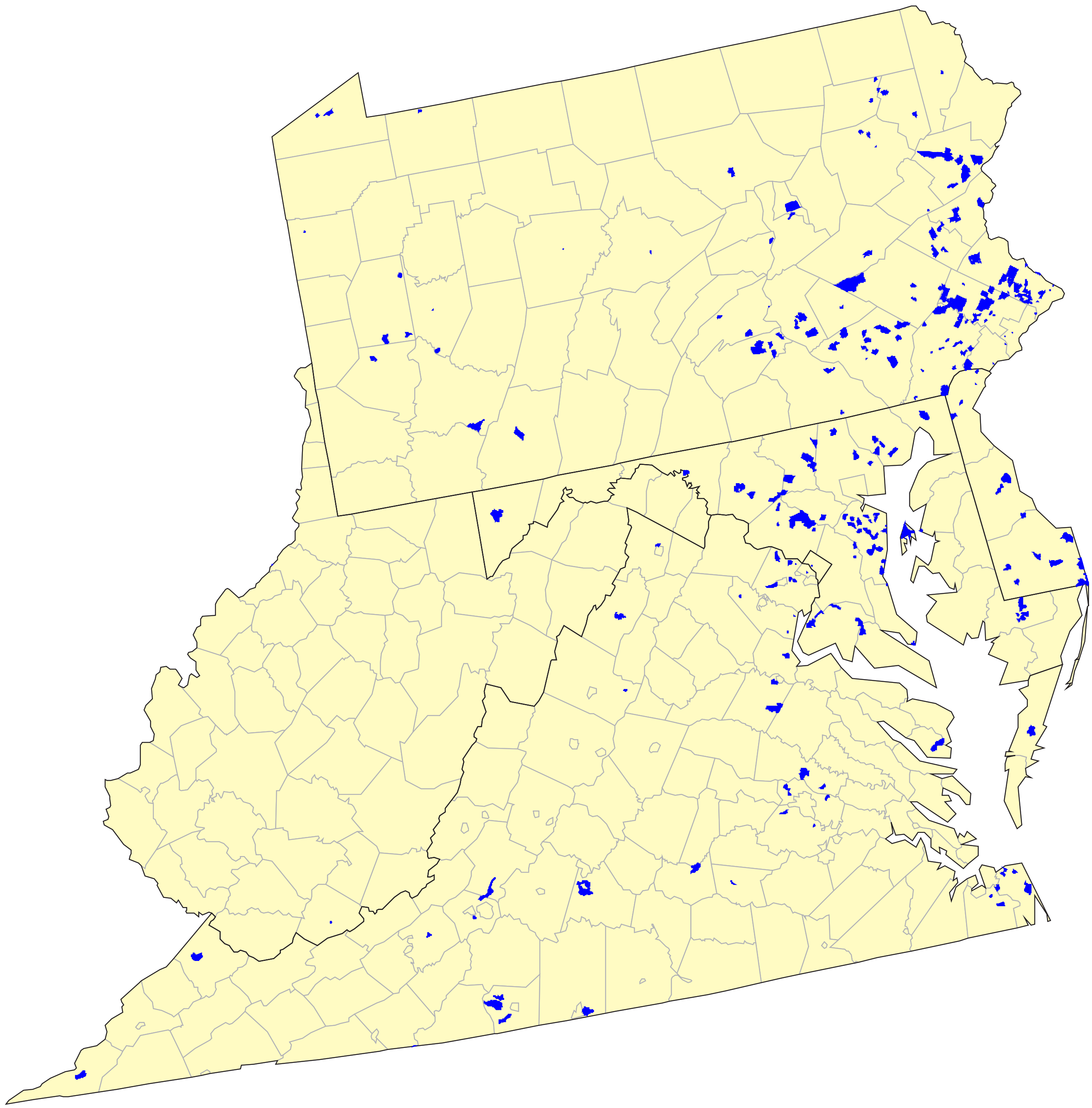
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

USEPA Region 3: Upper 1%

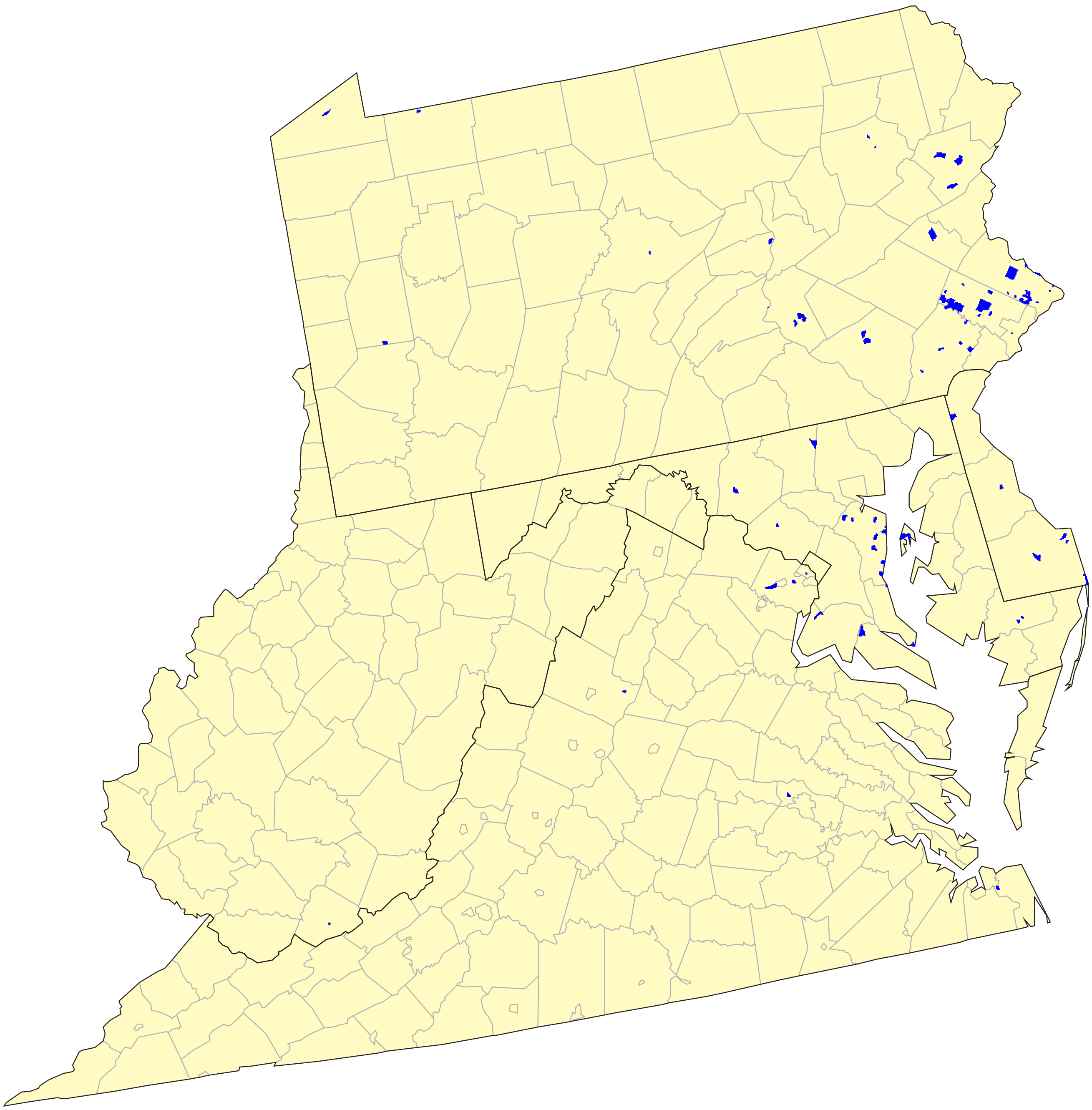
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 3: Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 3: Upper 10%

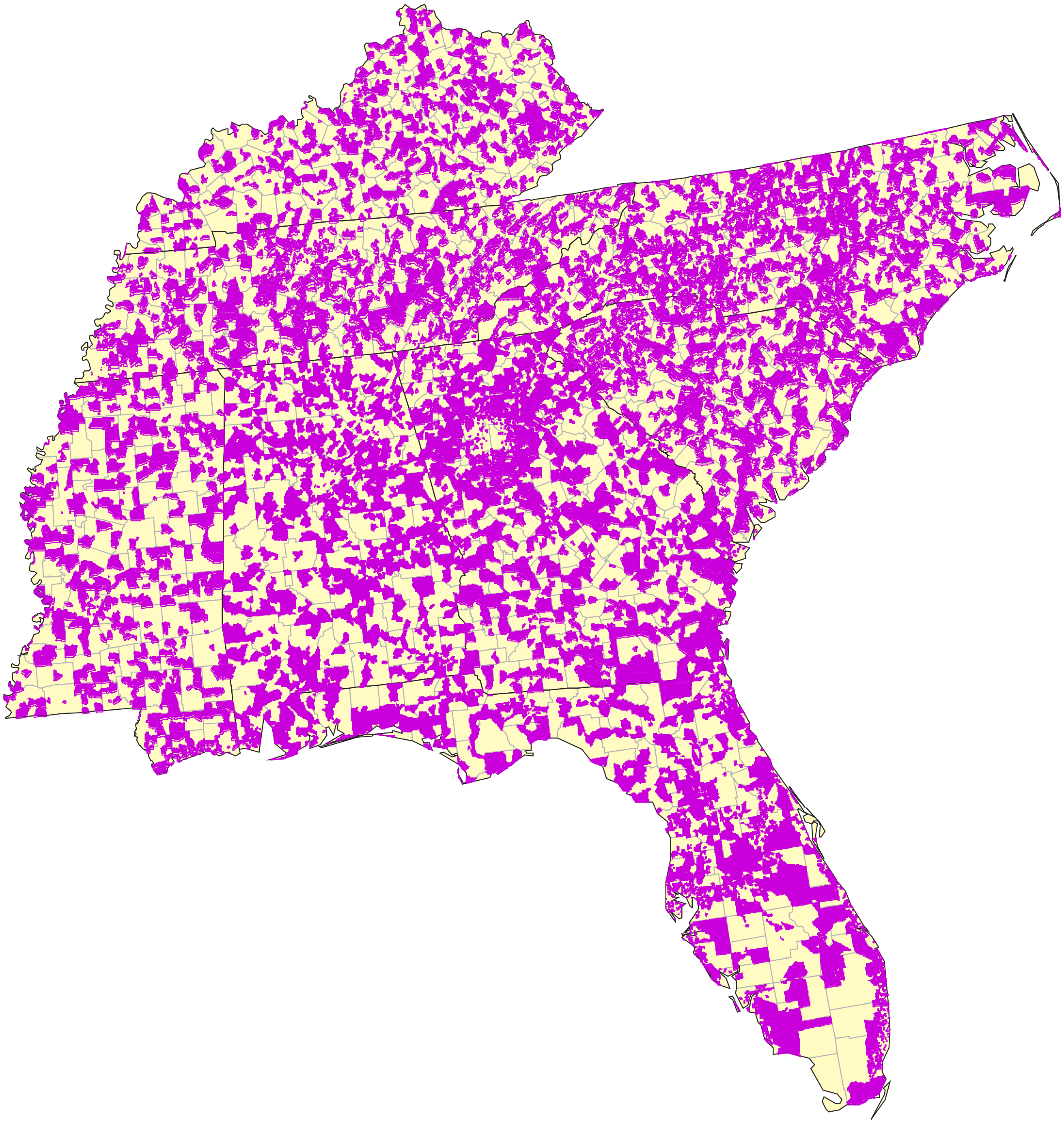


Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 3: Upper 3%

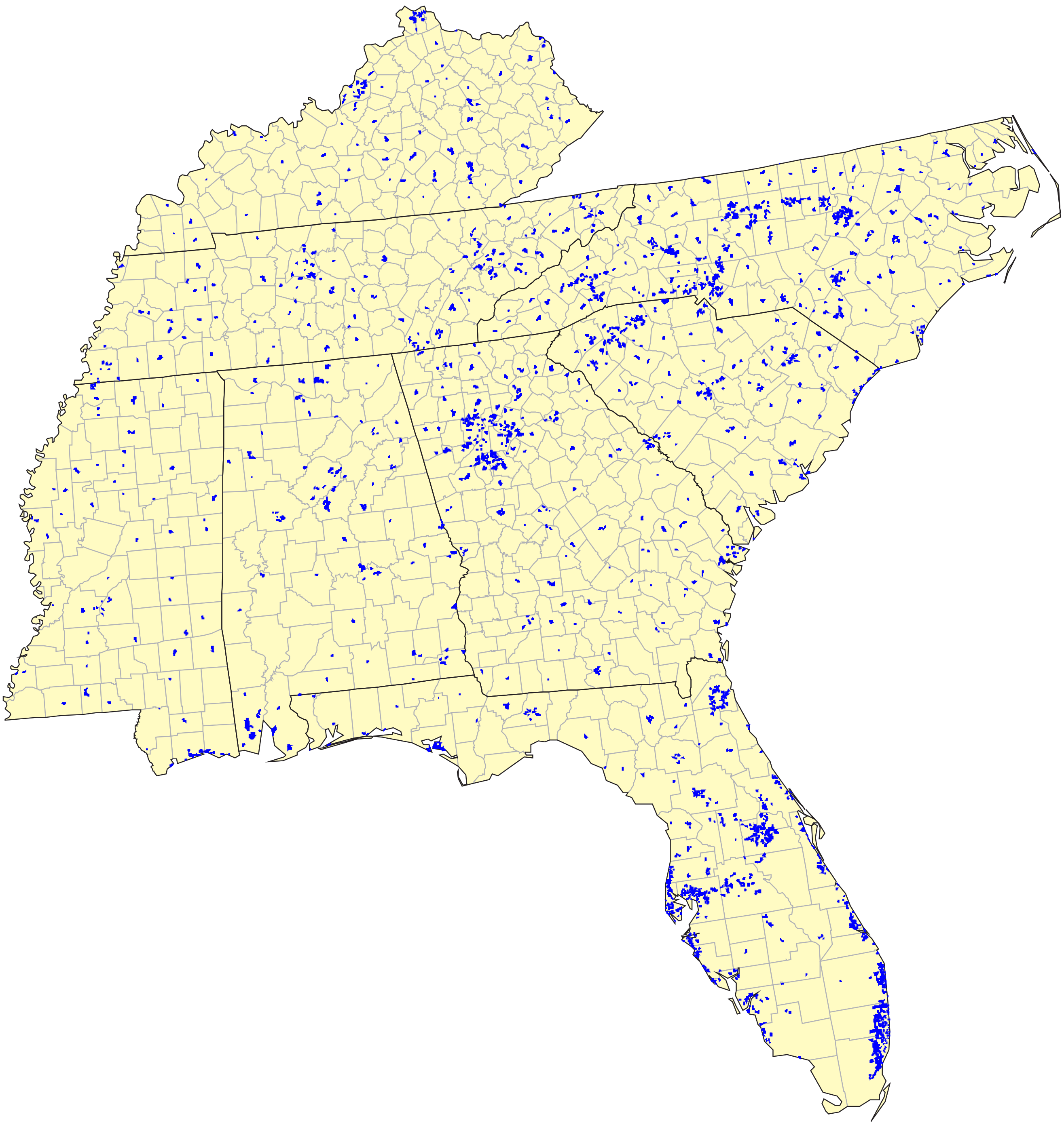
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 3: Upper 1%

Appendix E

USEPA Region 4 Vulnerability

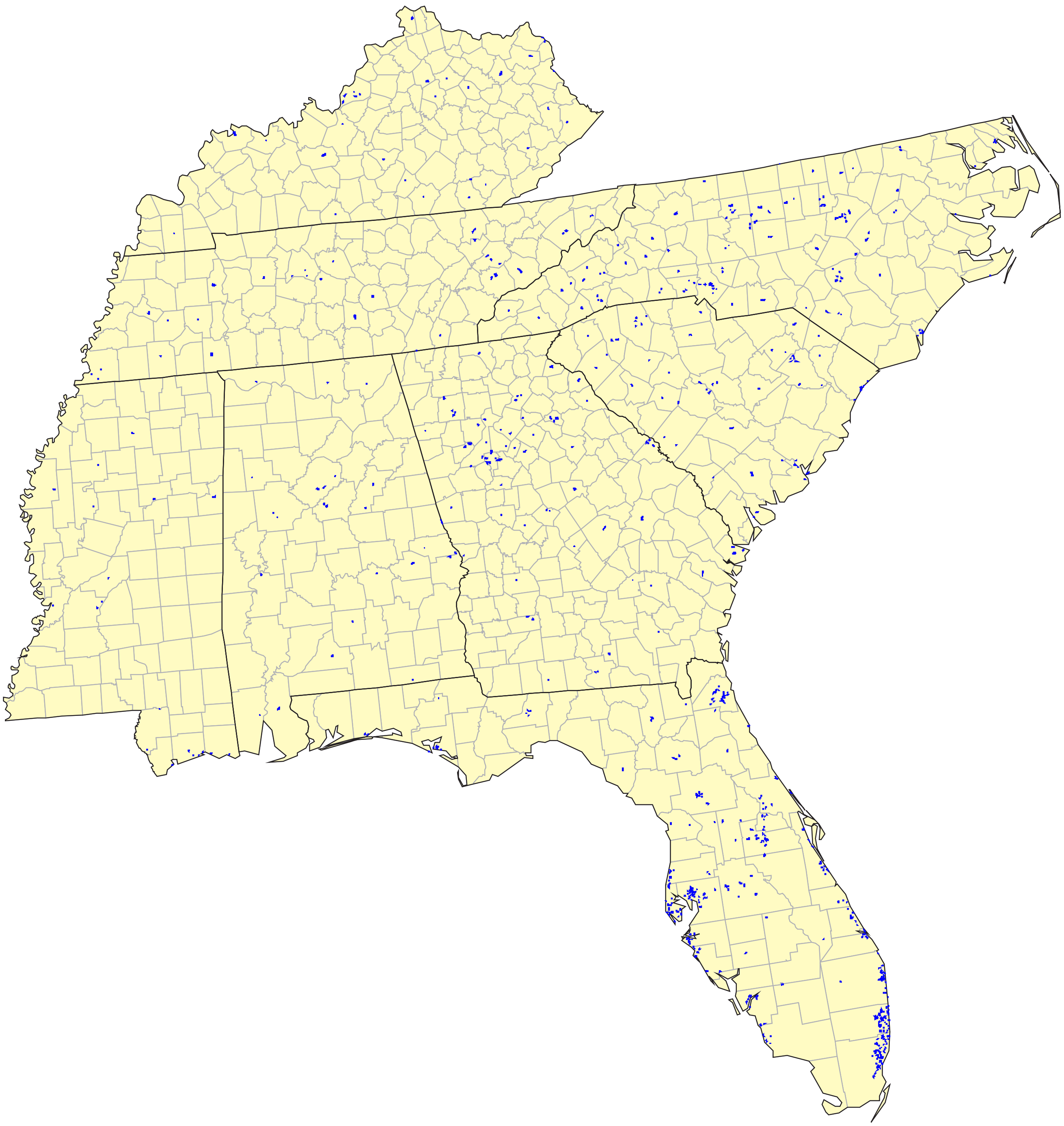


1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations



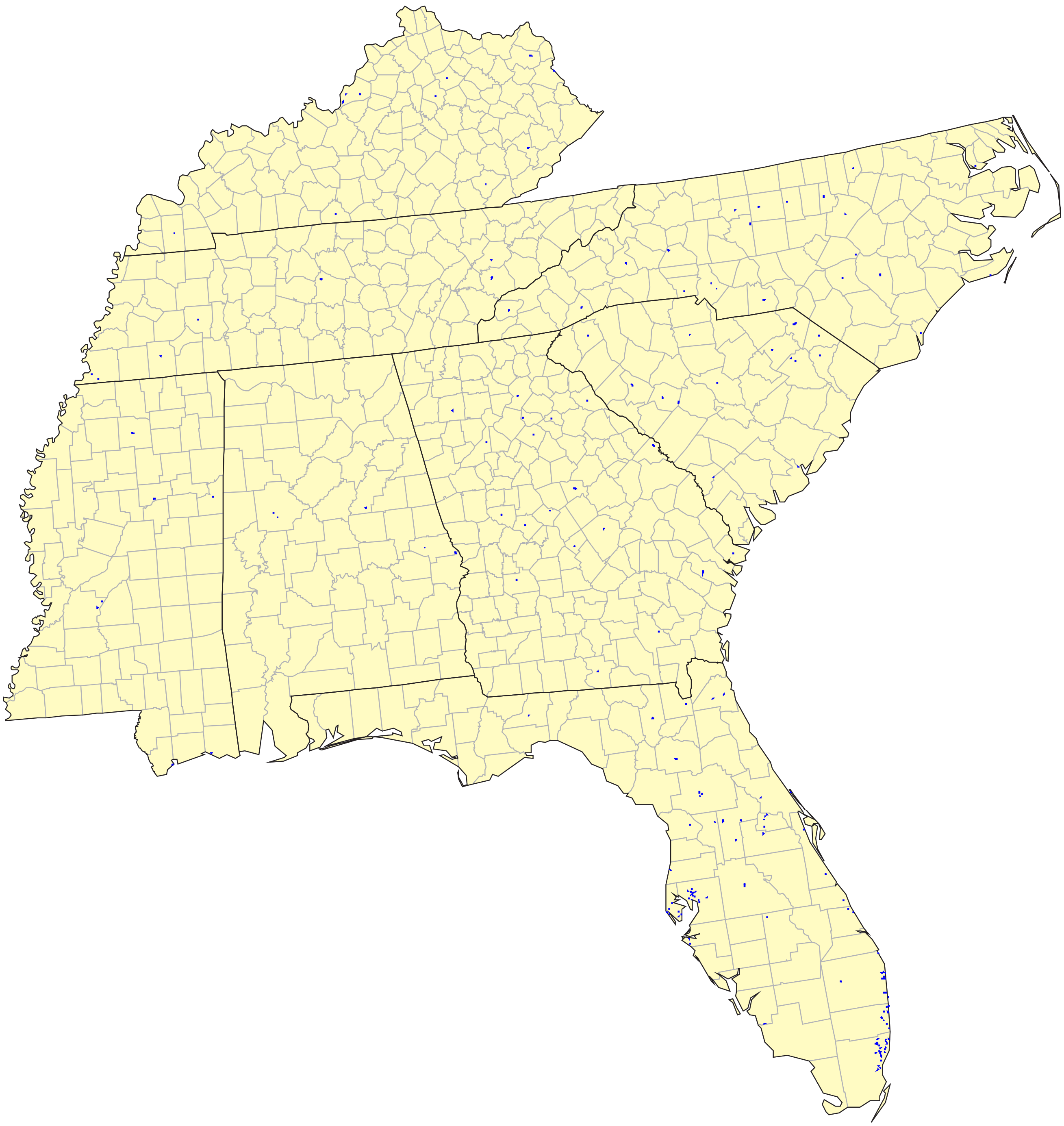
USEPA Region 4: Upper 30%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



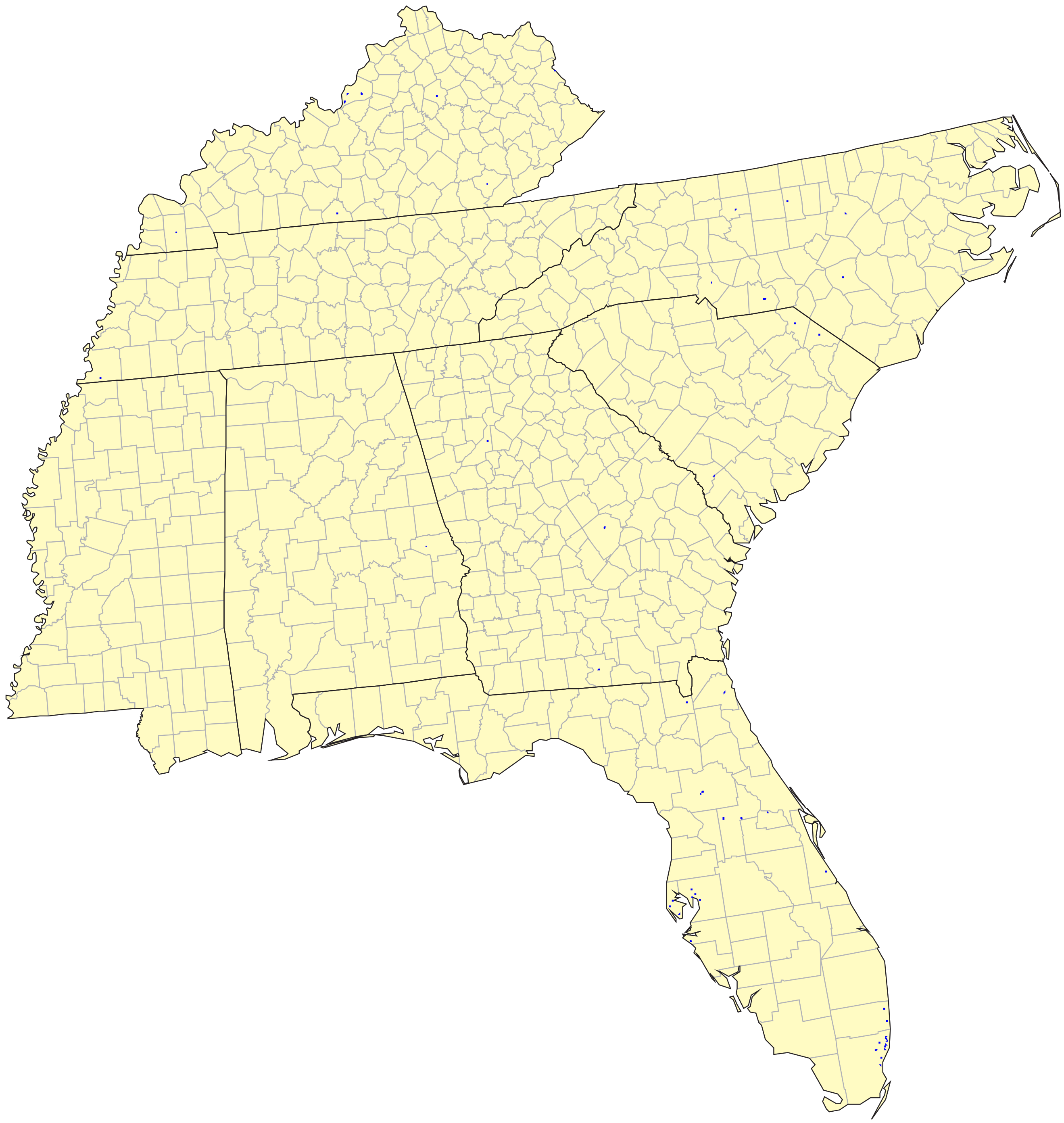
USEPA Region 4: Upper 10%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



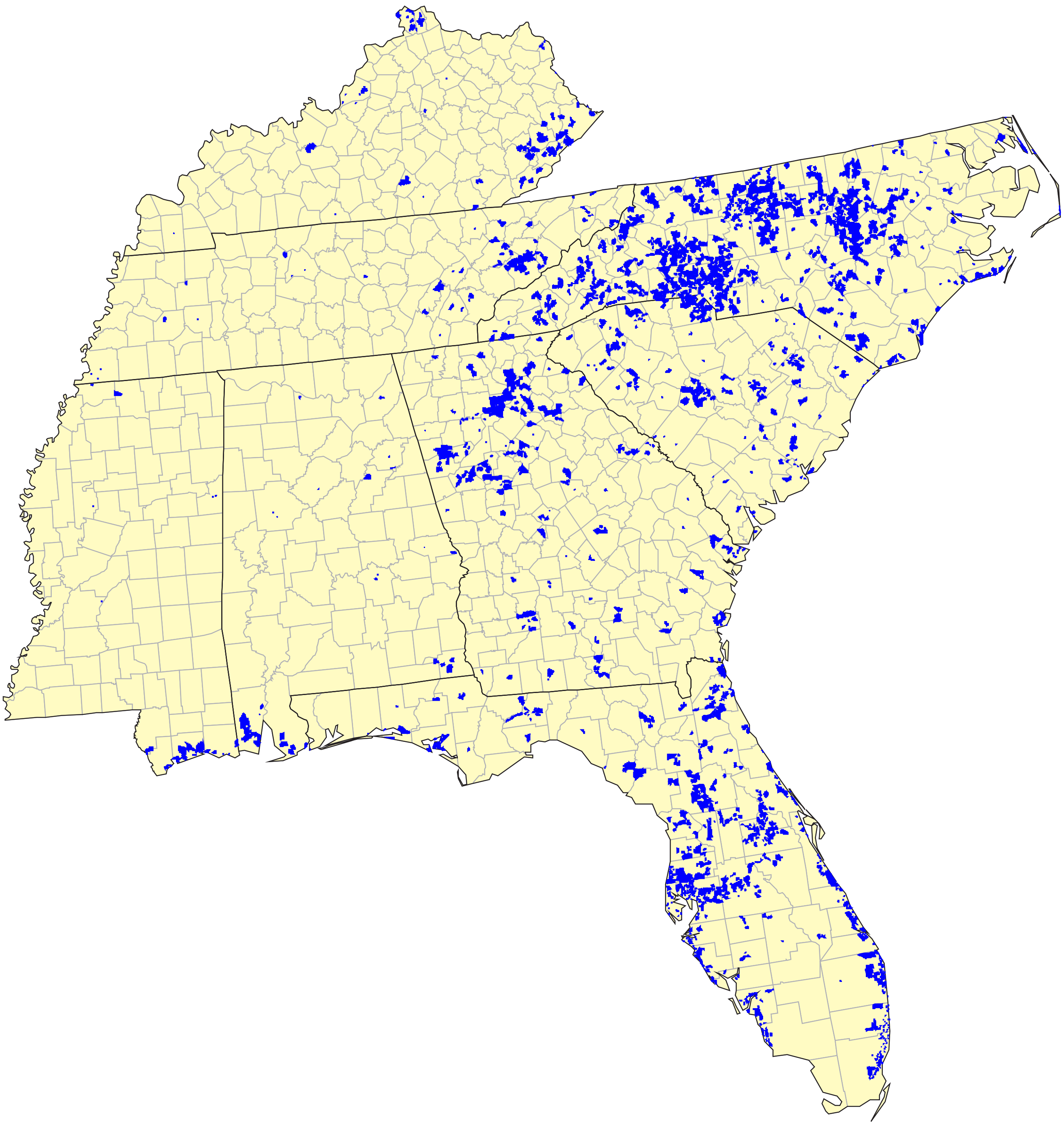
USEPA Region 4: Upper 3%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



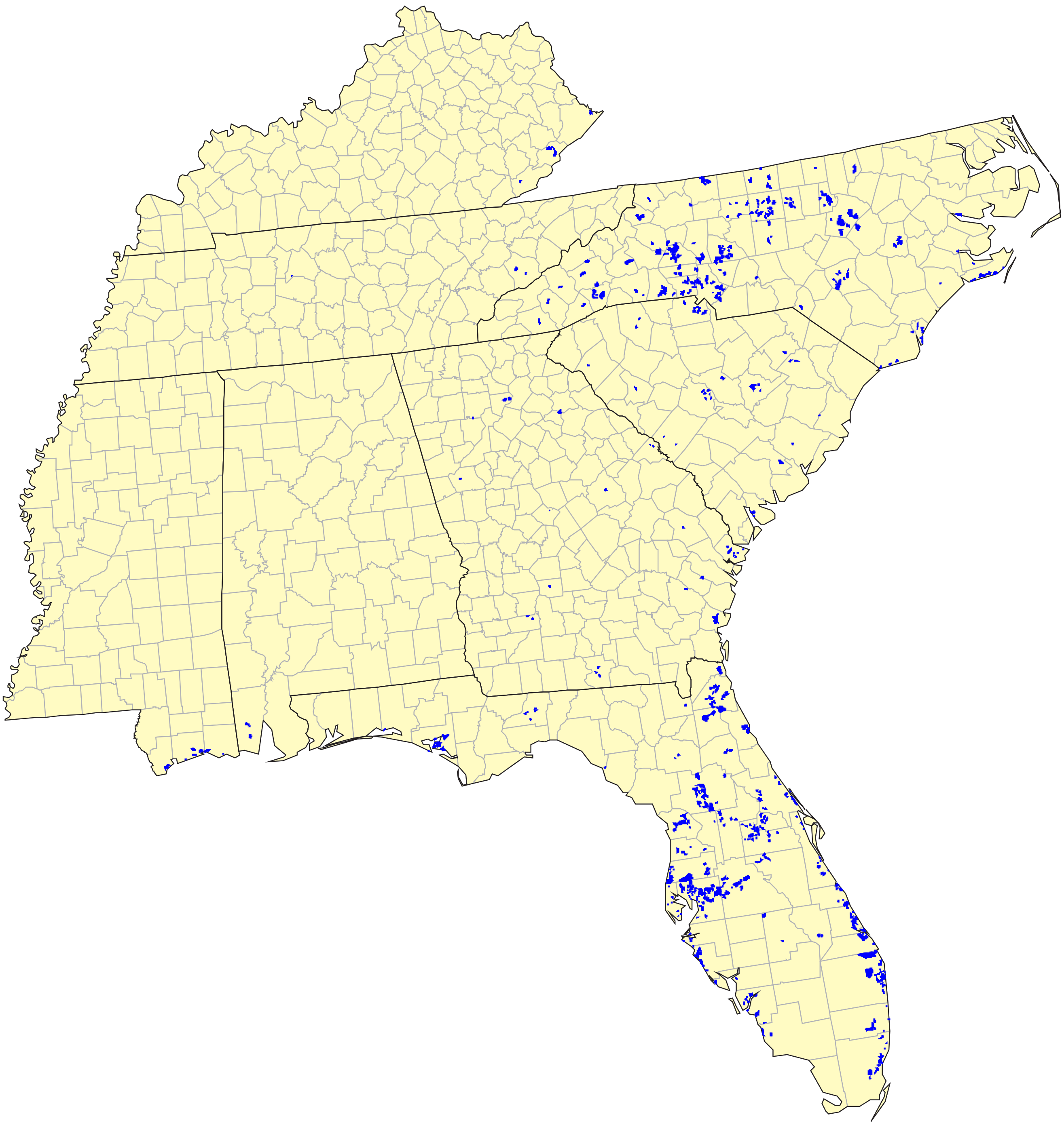
USEPA Region 4: Upper 1%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



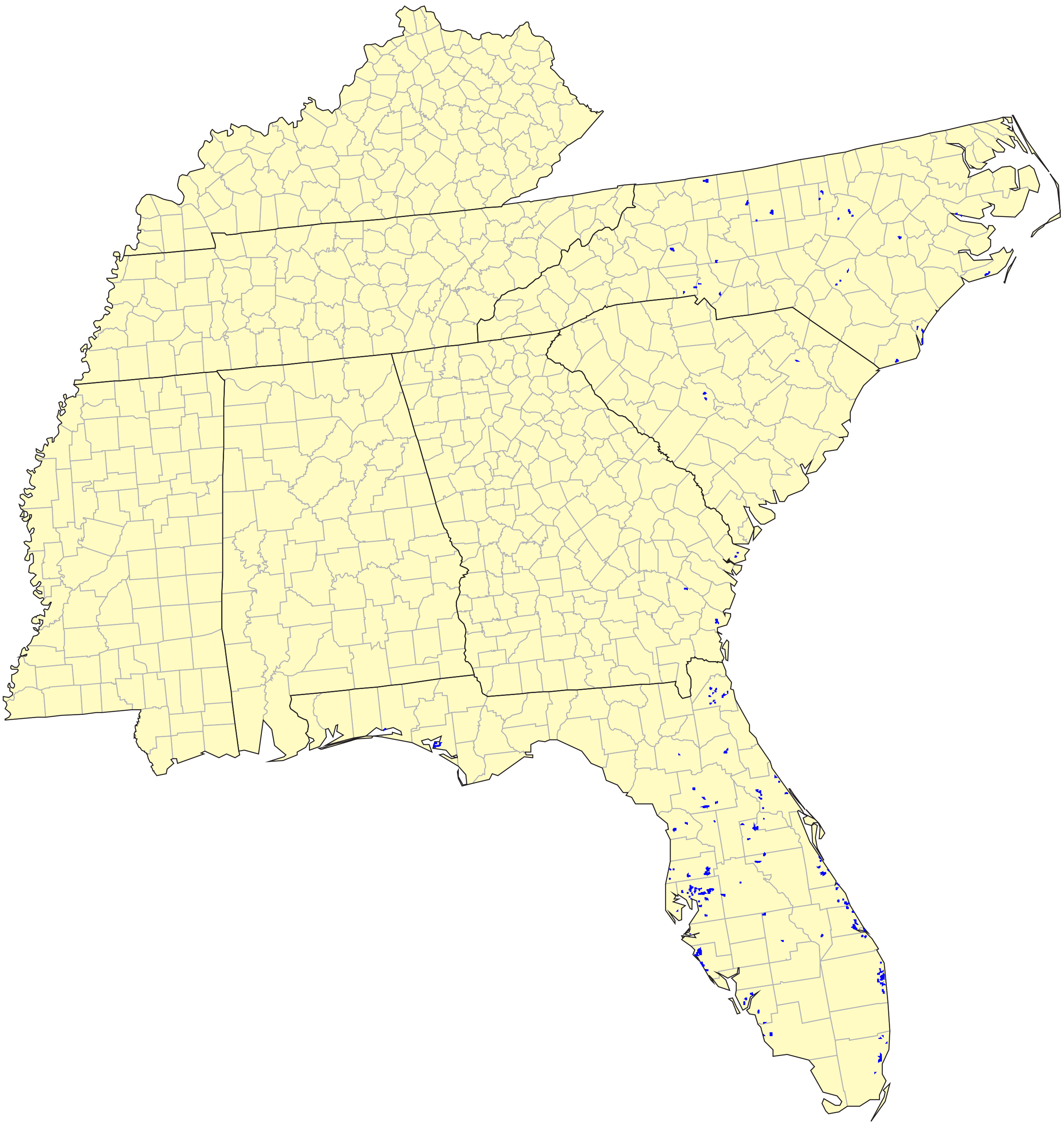
USEPA Region 4: Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



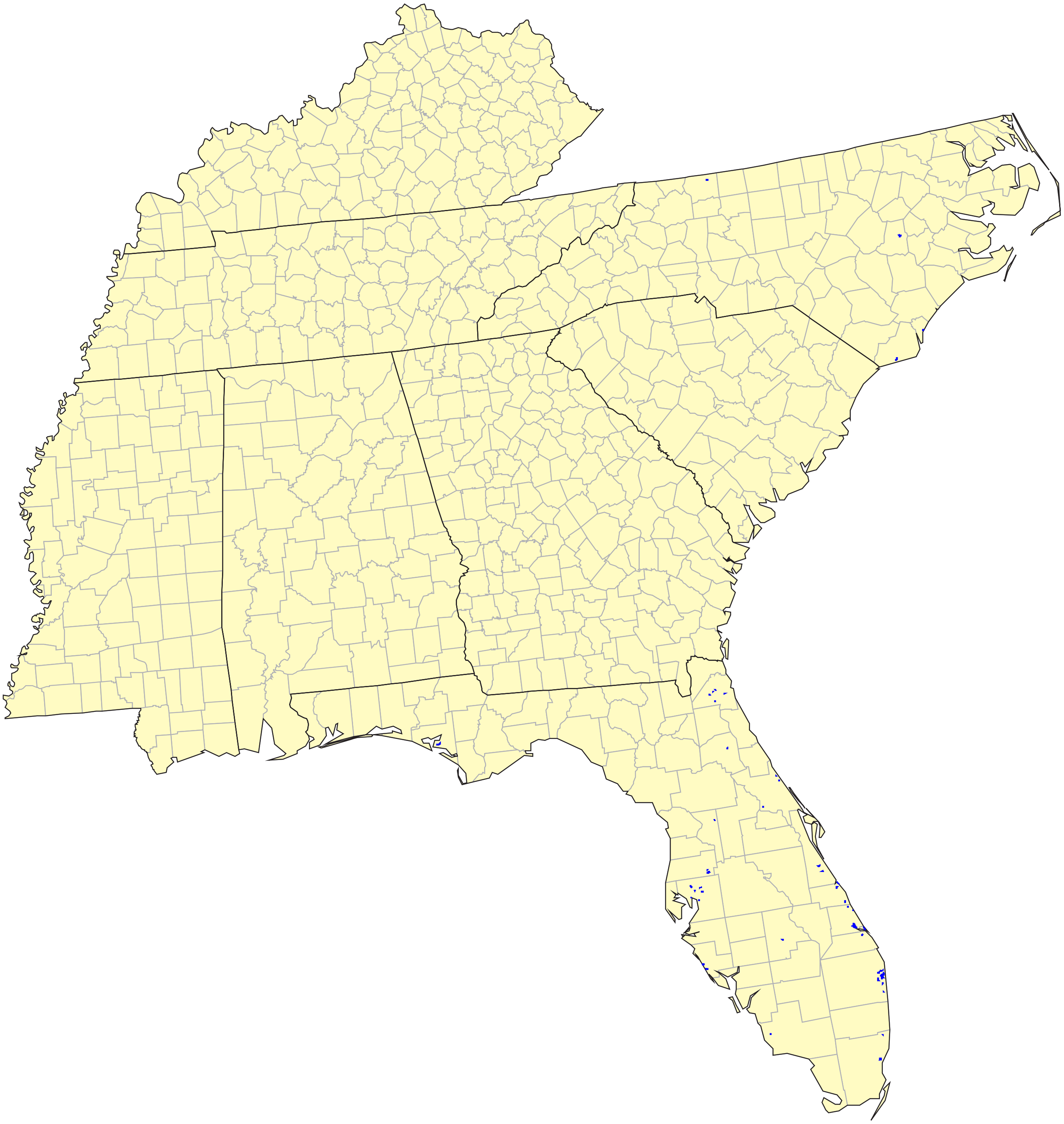
USEPA Region 4: Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



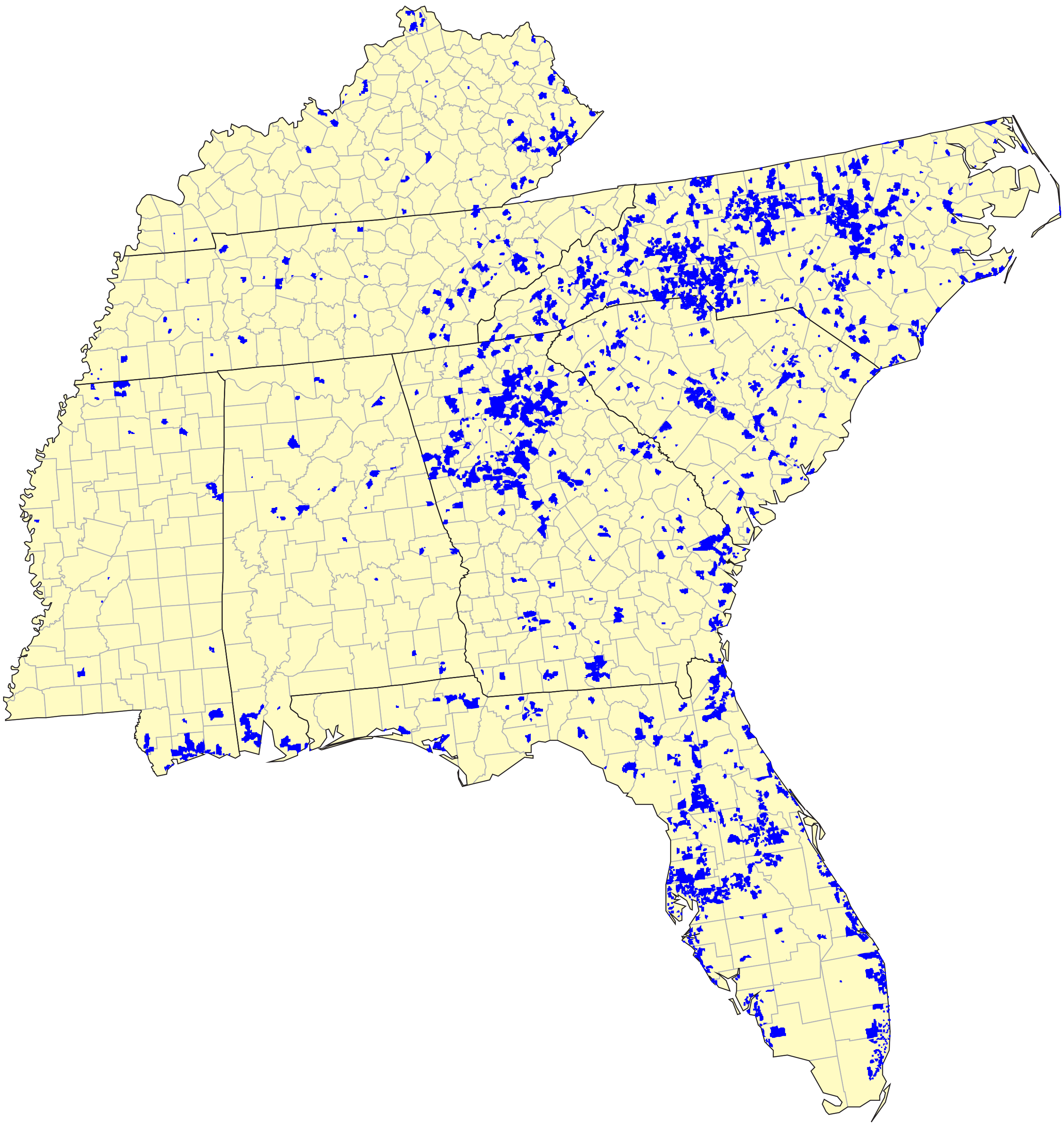
USEPA Region 4: Upper 3%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

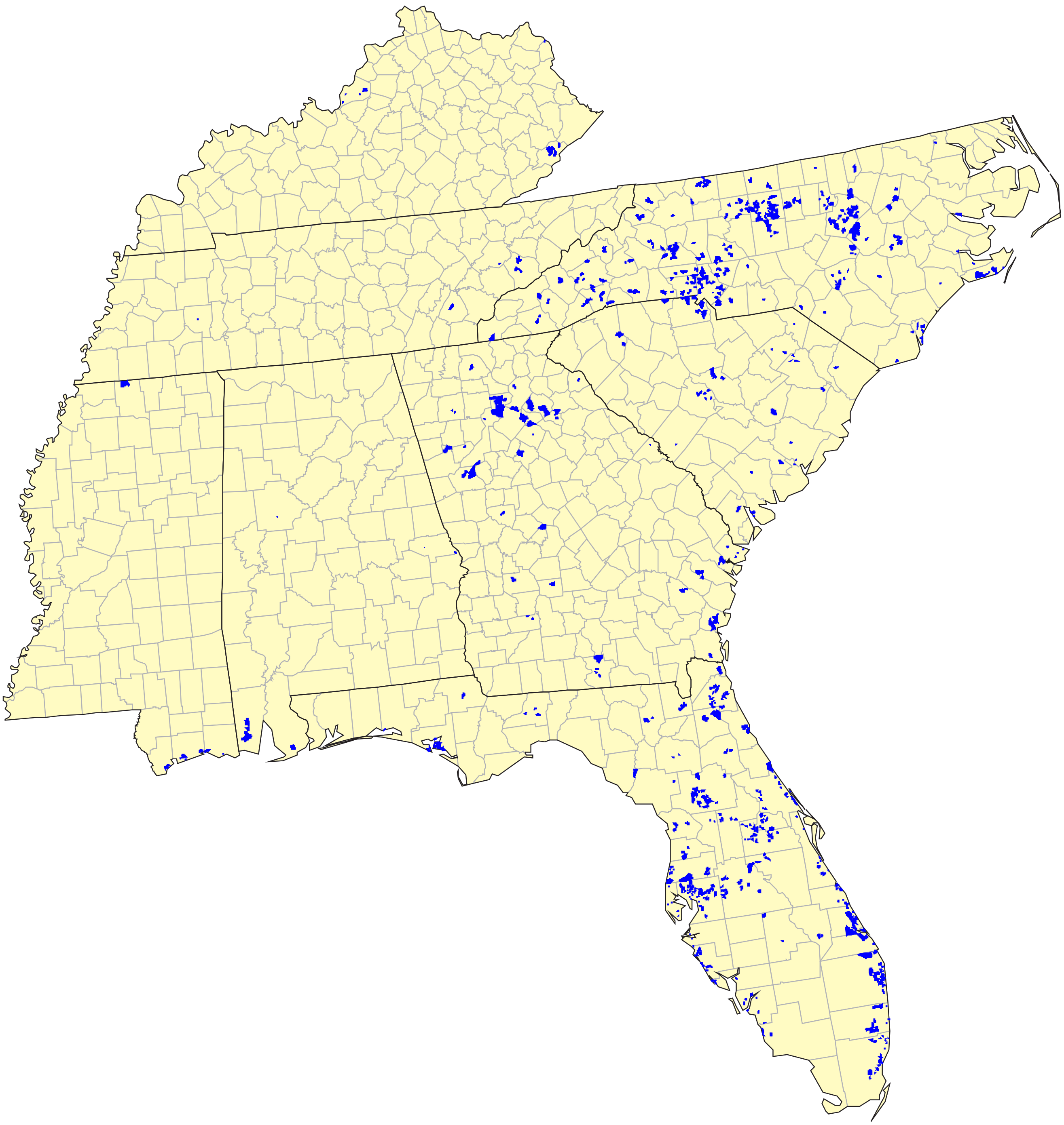


USEPA Region 4: Upper 1%

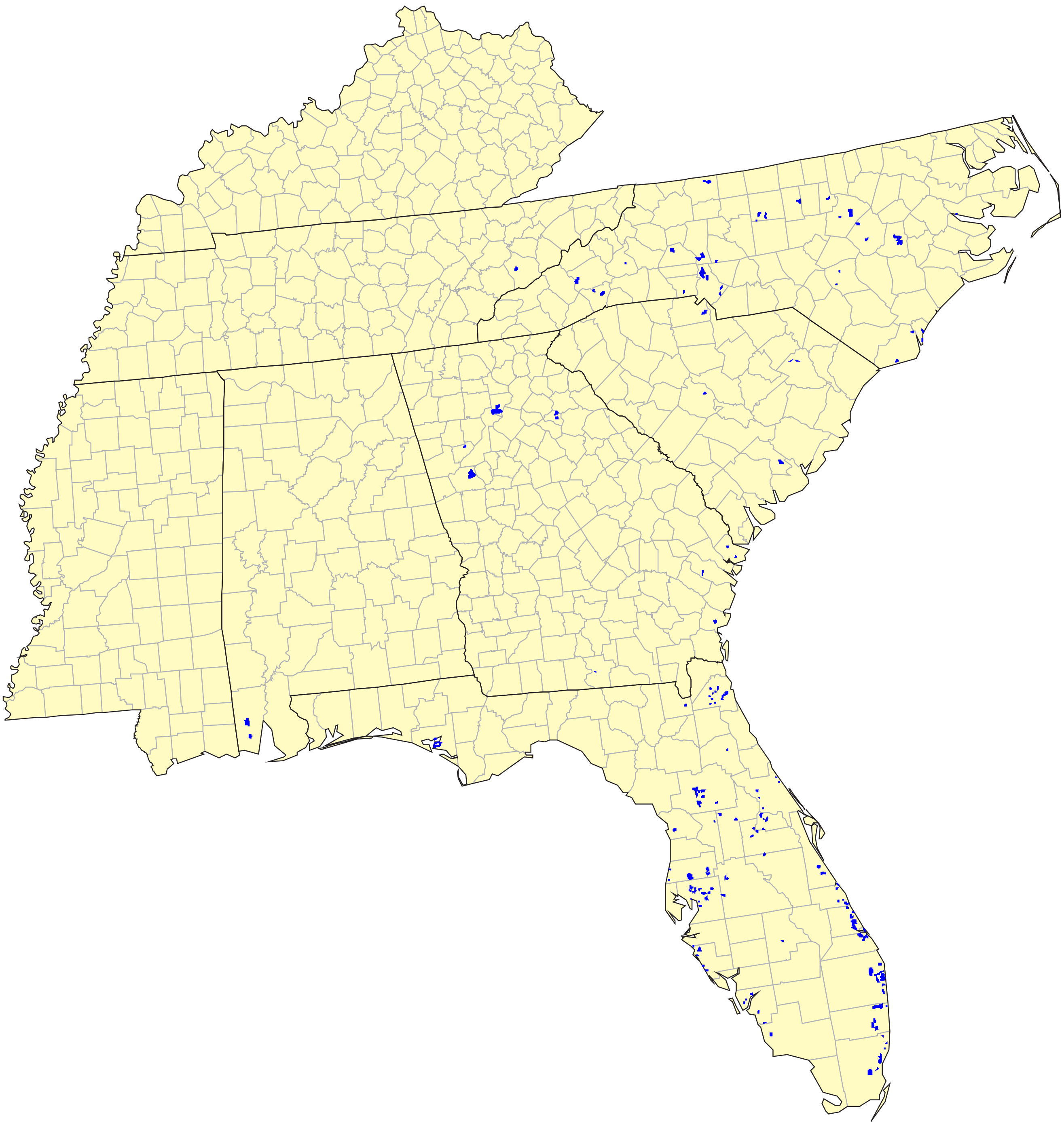
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



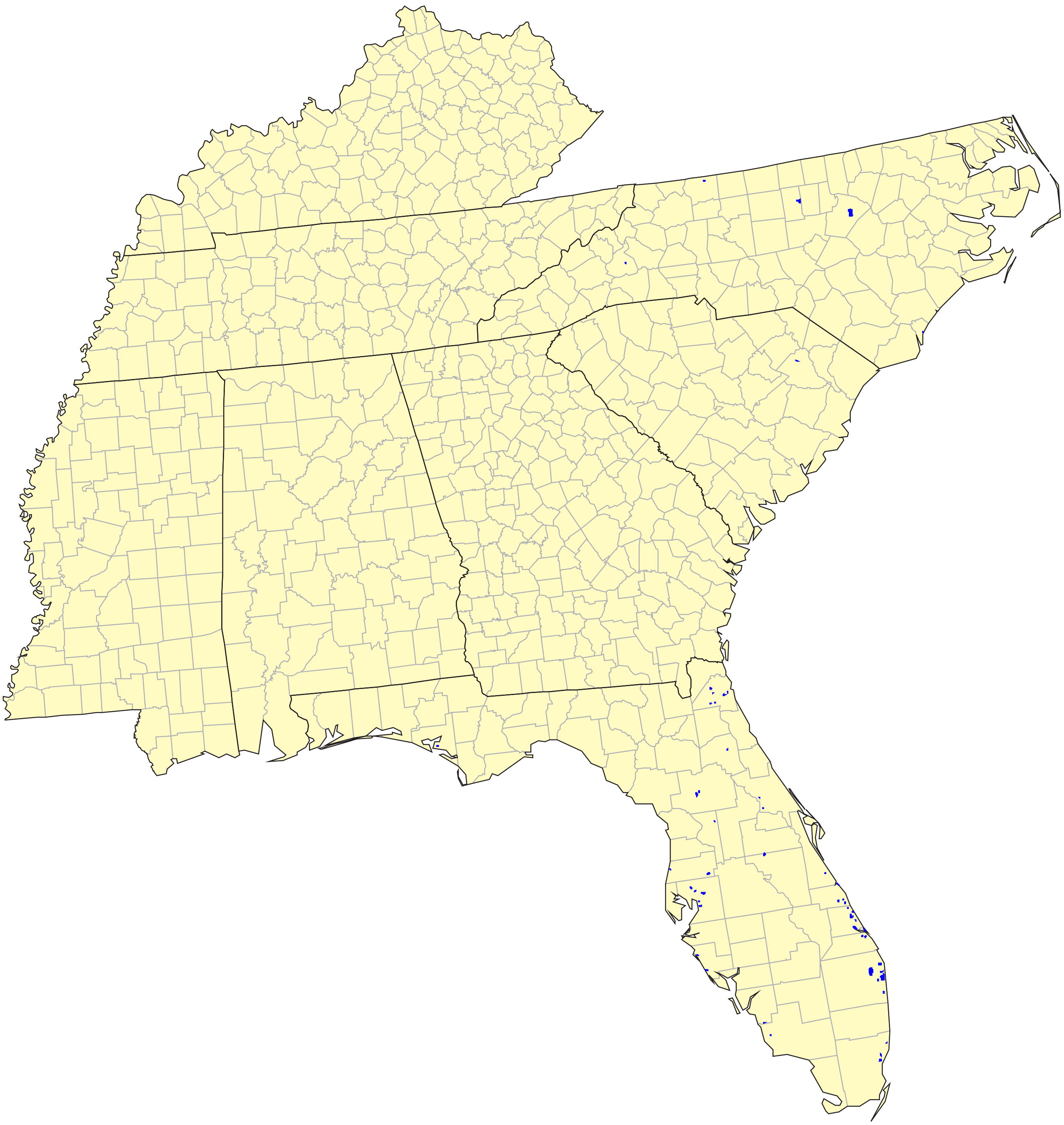
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 4: Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 4: Upper 10%



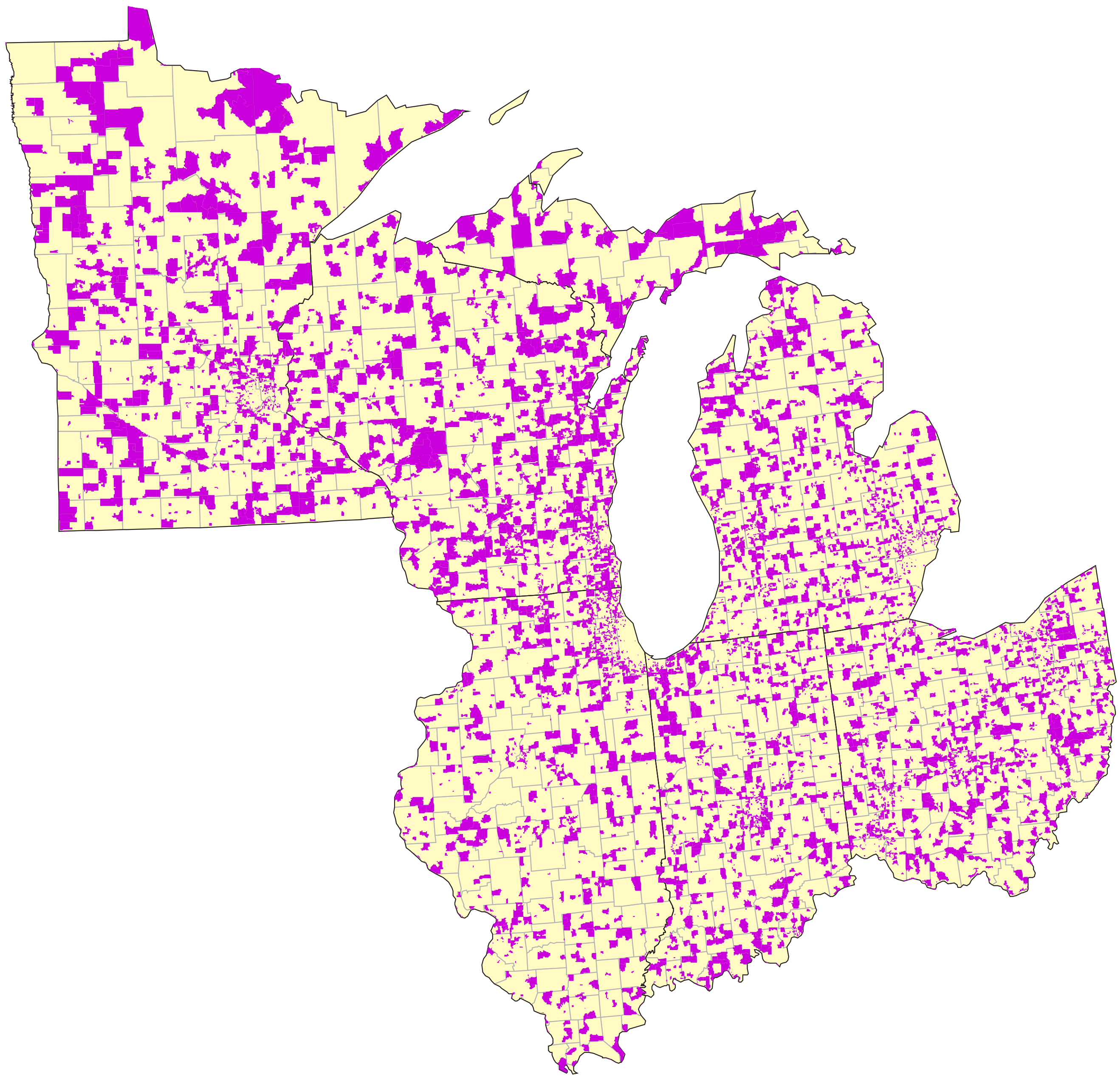
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 4: Upper 3%



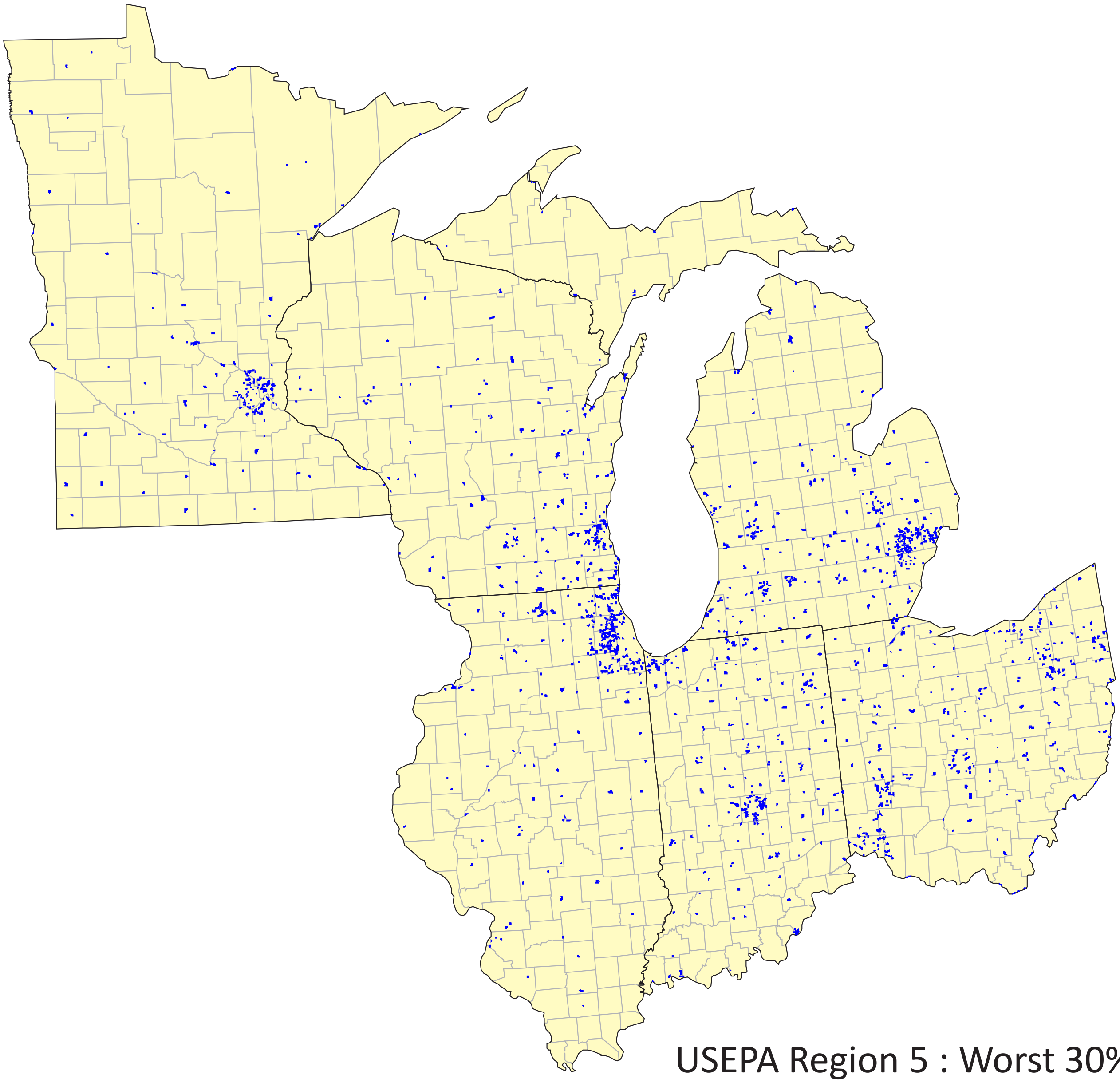
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 4: Upper 1%

Appendix F

USEPA Region 5 Vulnerability

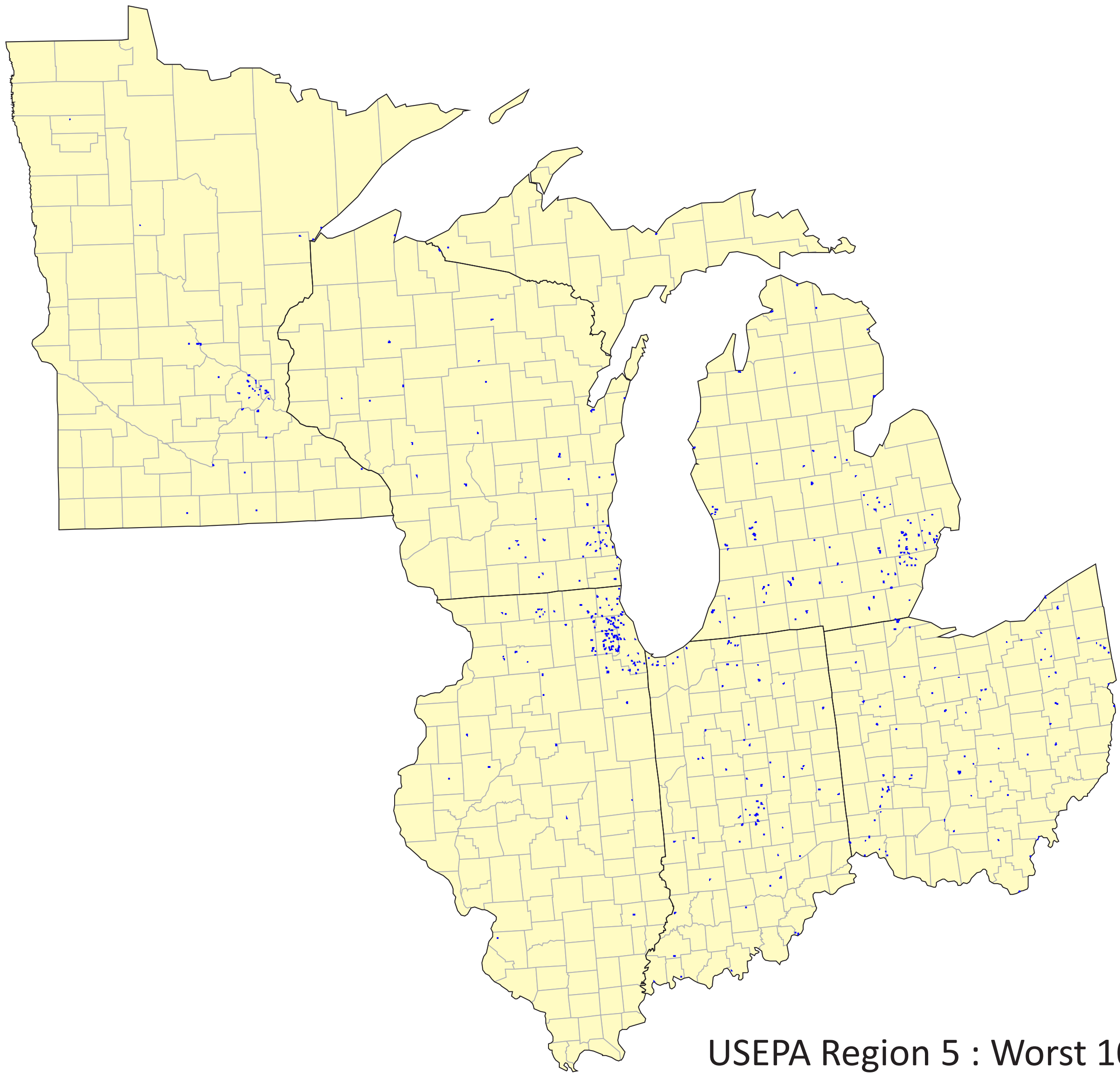


1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water AND Service Stations



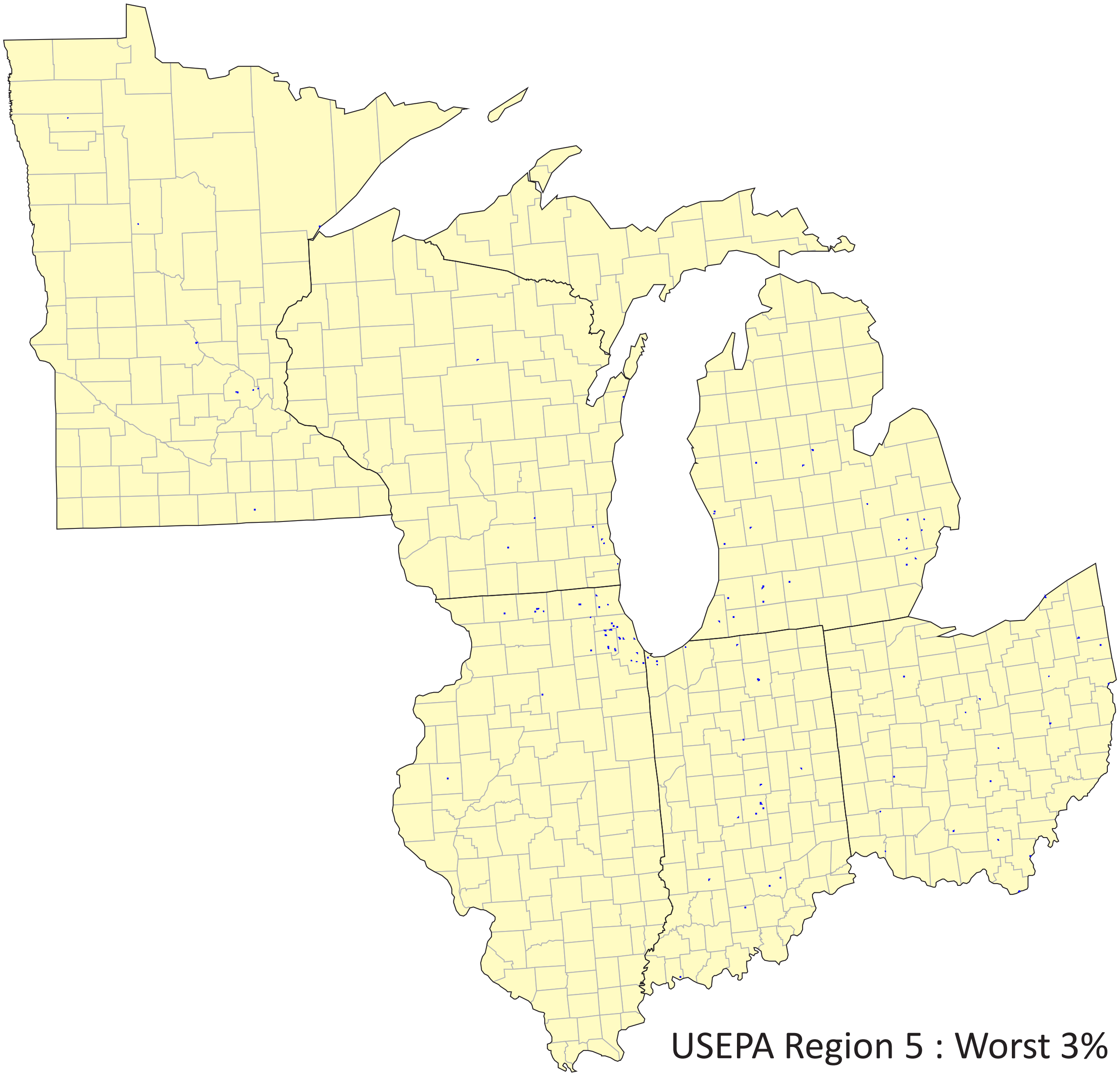
USEPA Region 5 : Worst 30%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



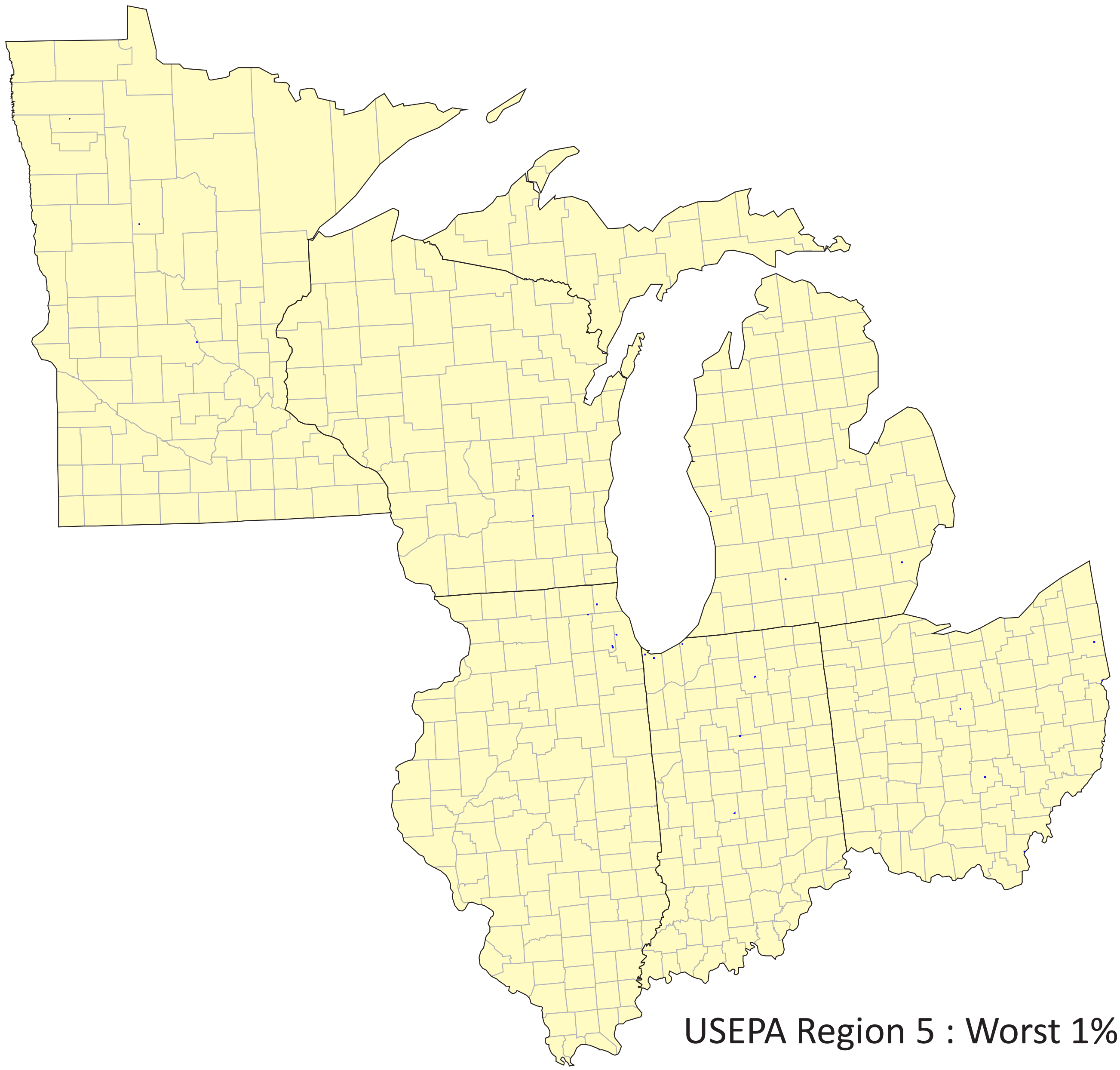
USEPA Region 5 : Worst 10%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)

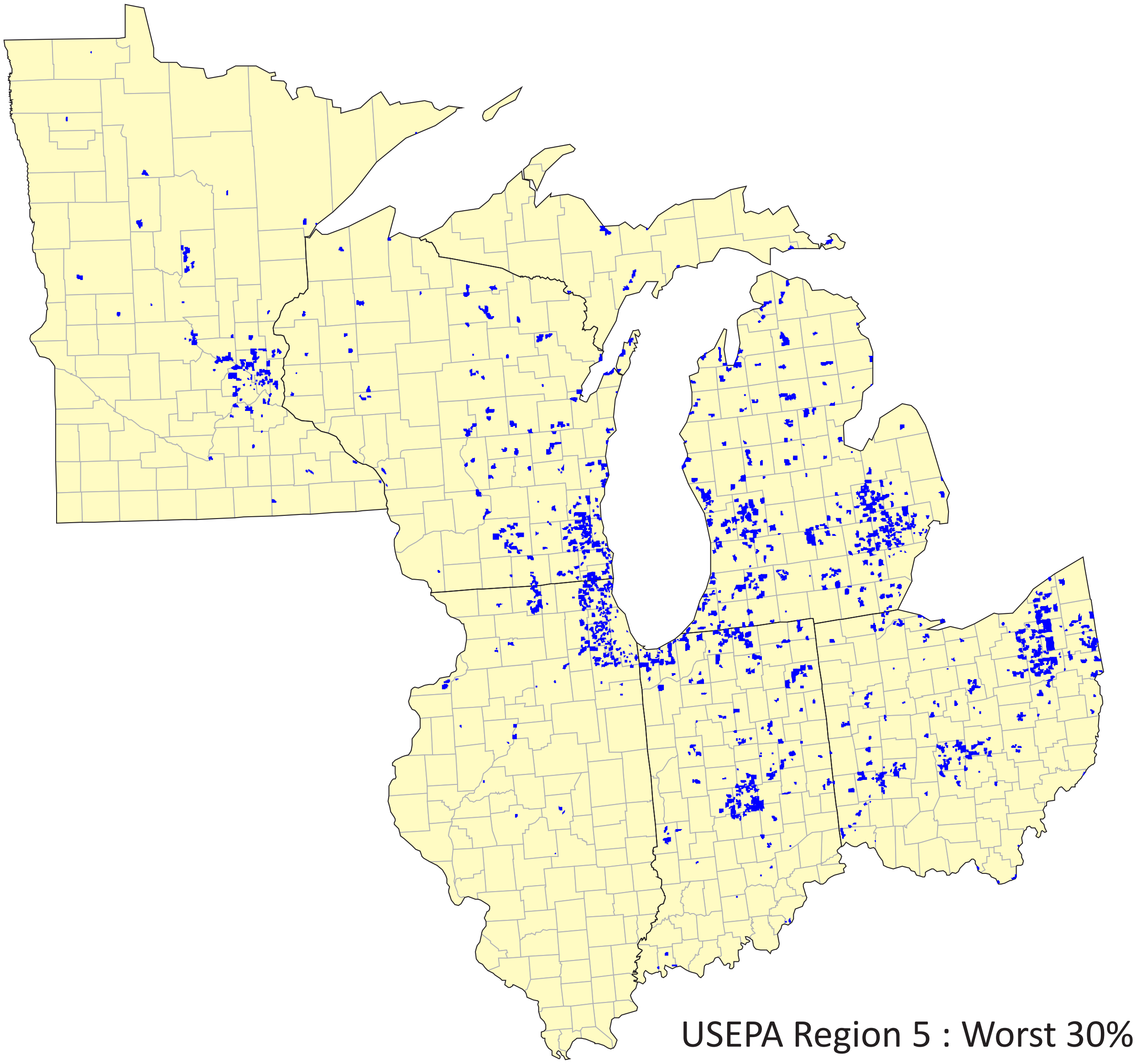


USEPA Region 5 : Worst 3%

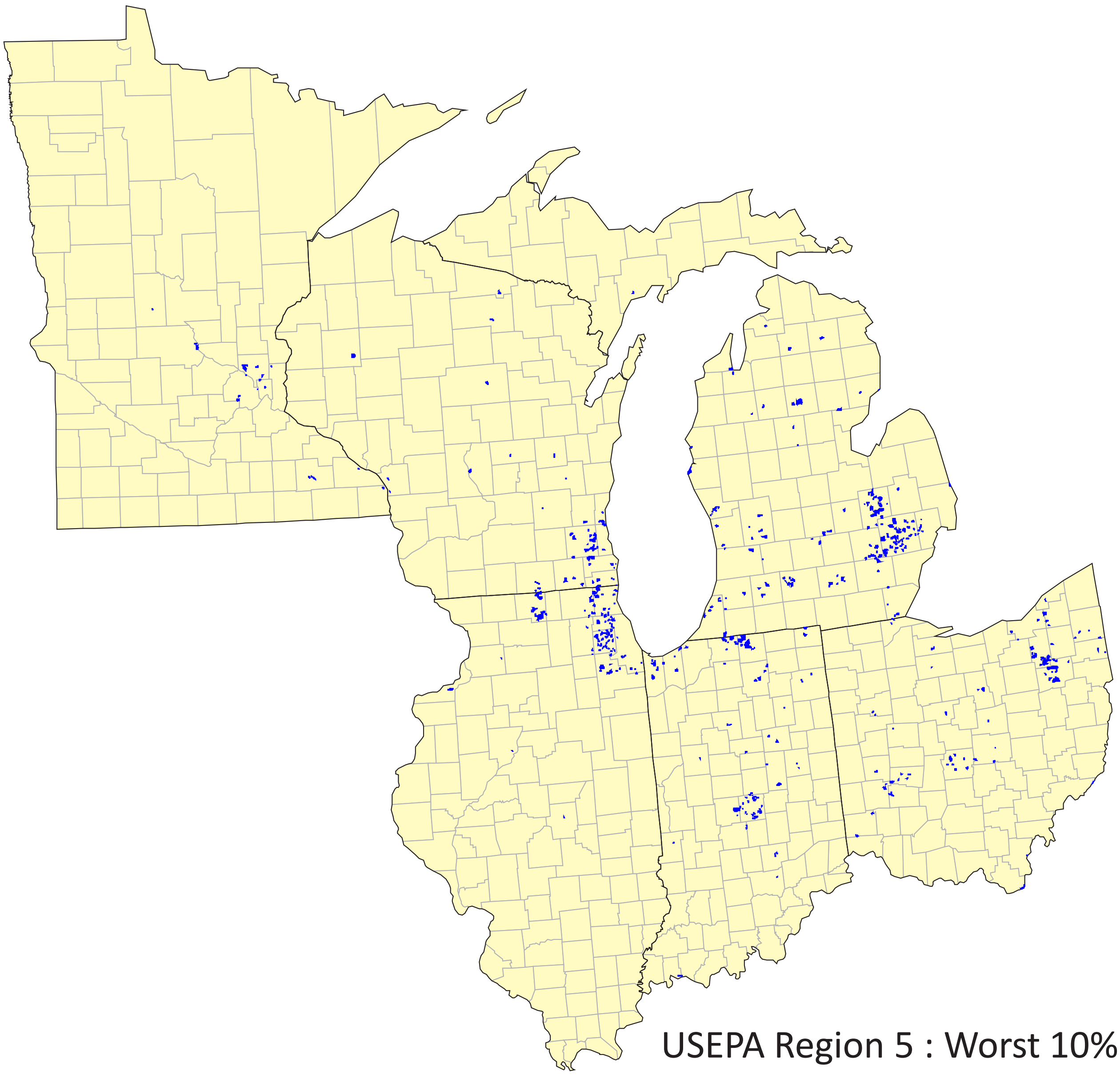
Vulnerability Index 1: Density of Service Stations
(stations per square mile)



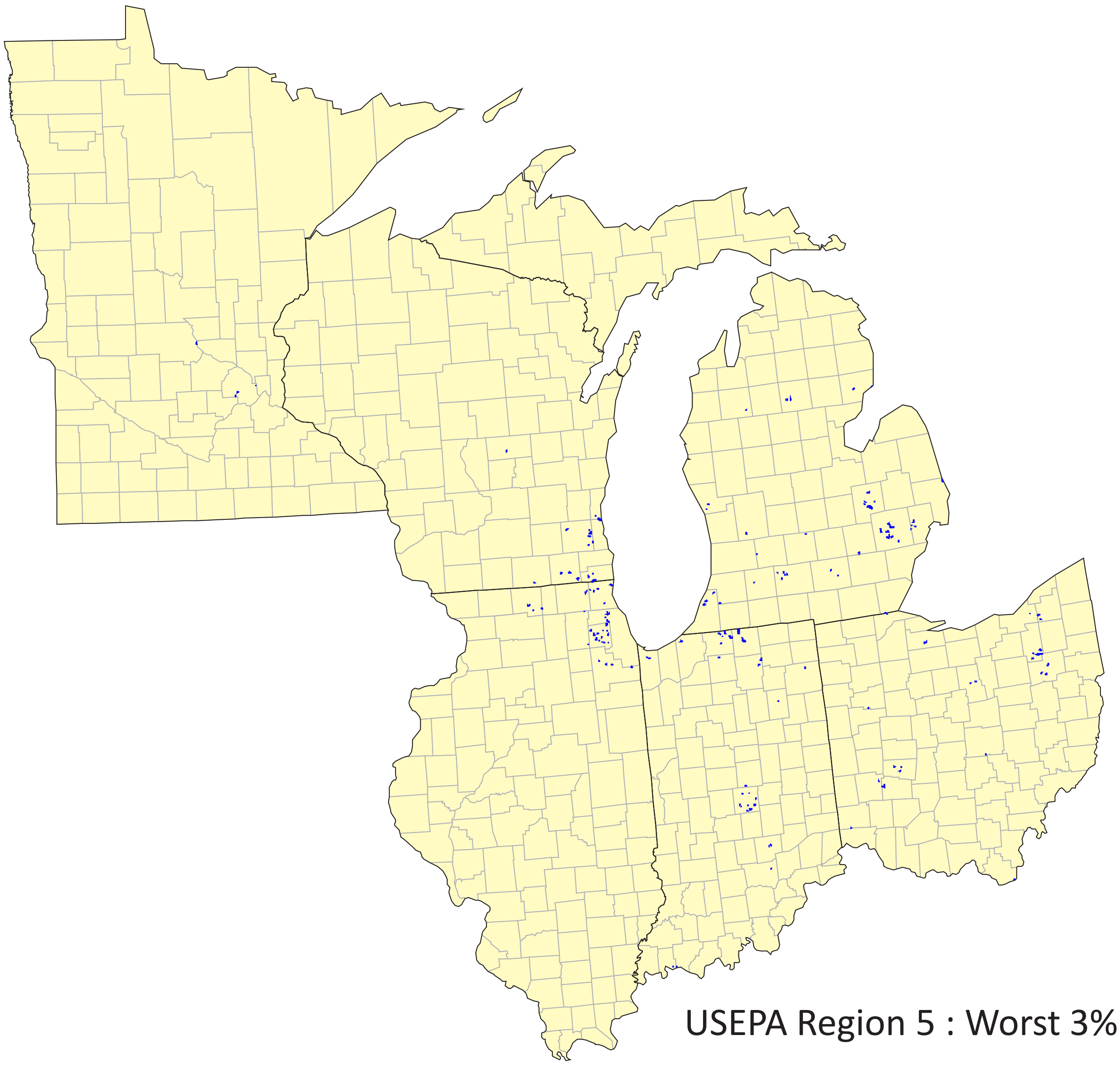
Vulnerability Index 1: Density of Service Stations
(stations per square mile)



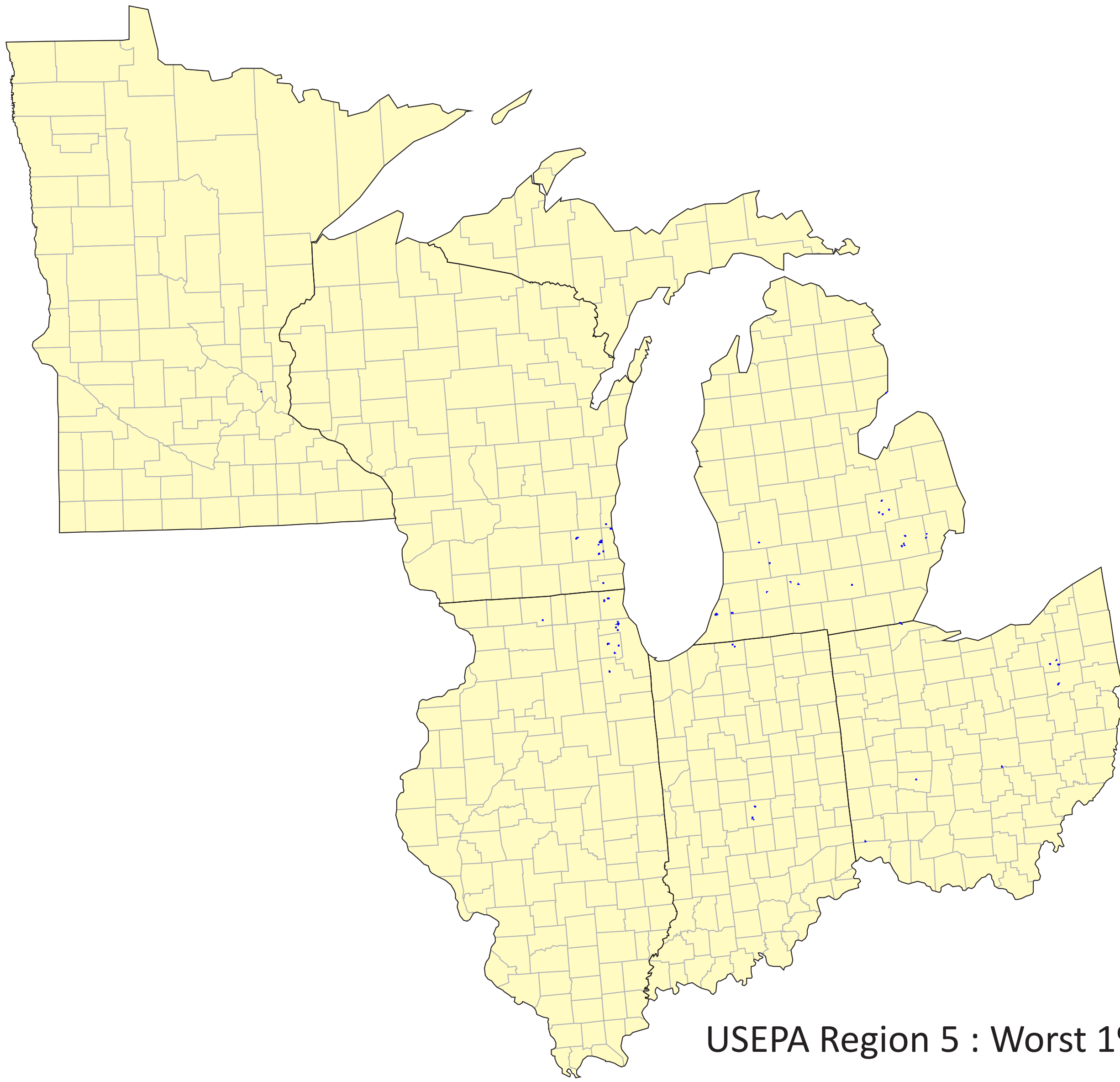
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



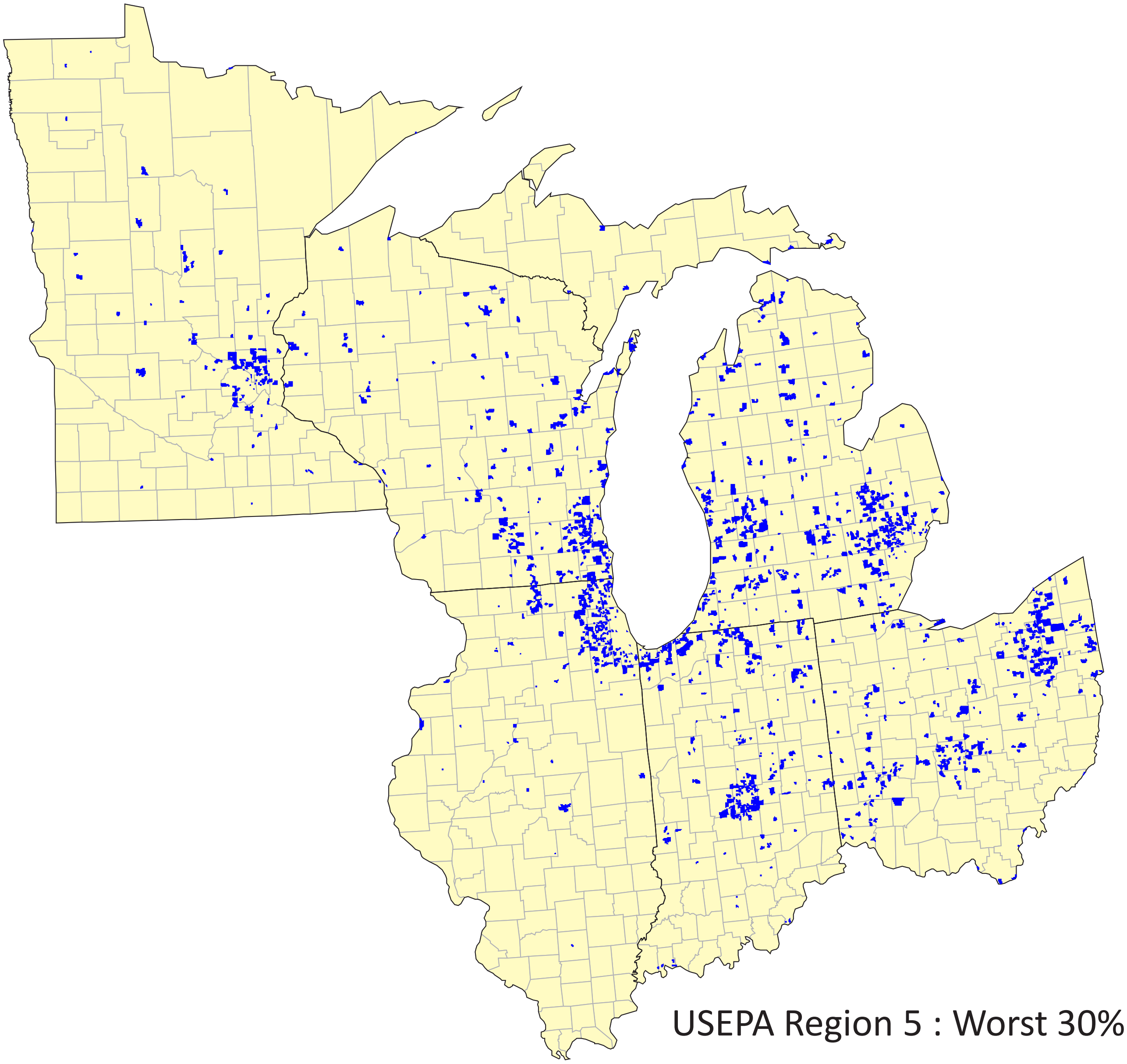
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



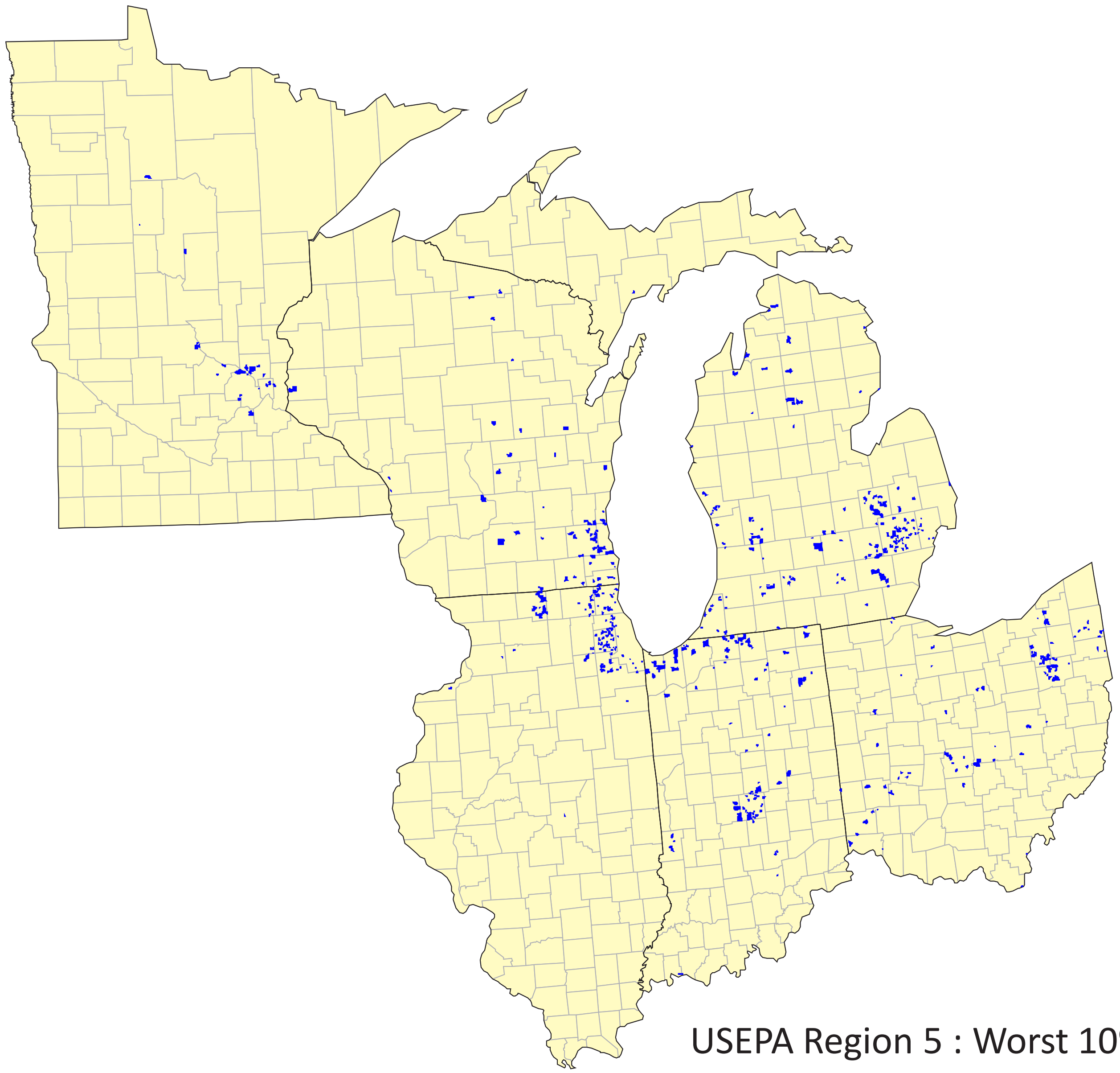
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

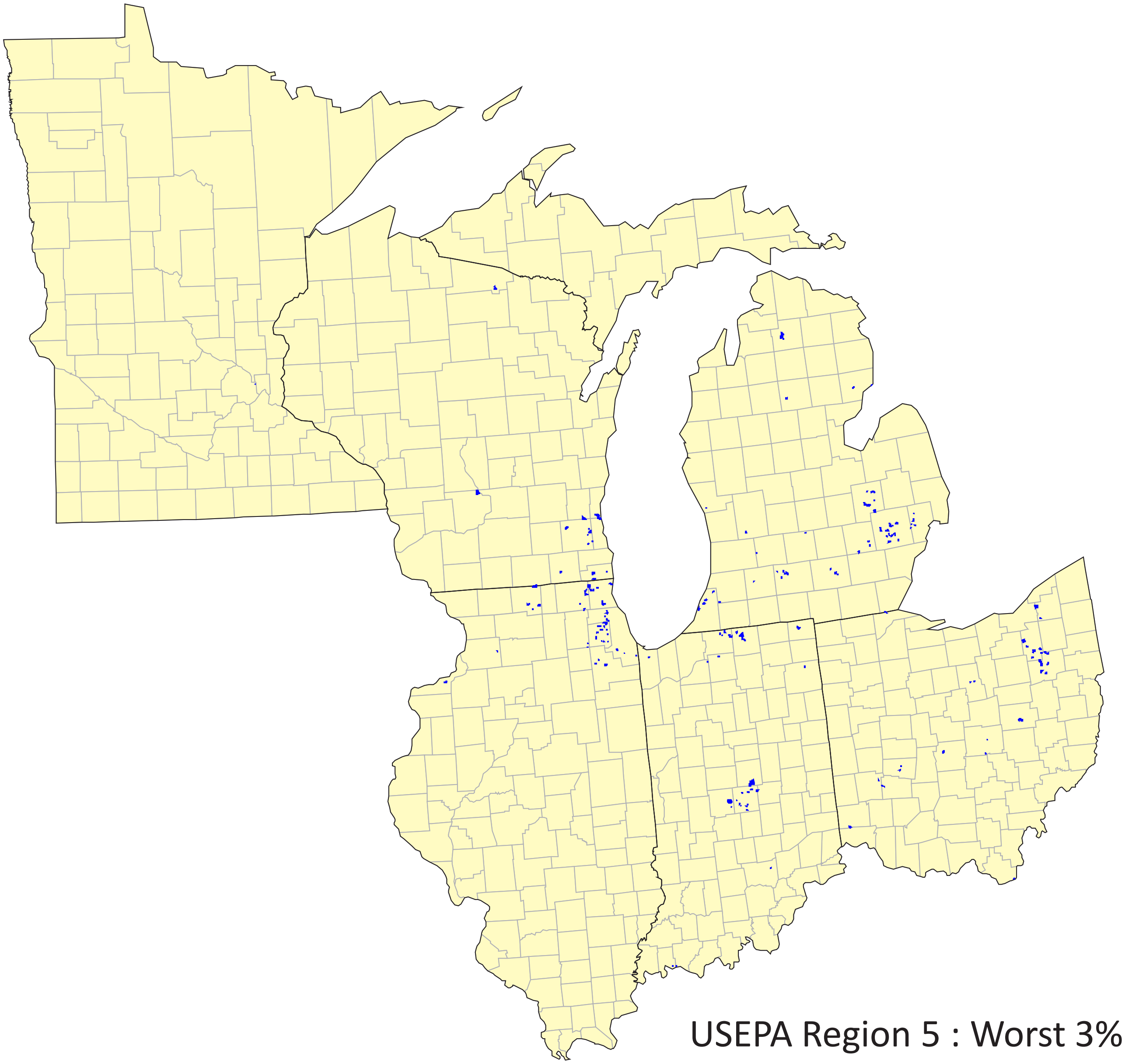


Vulnerability Index 3: $\dfrac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$

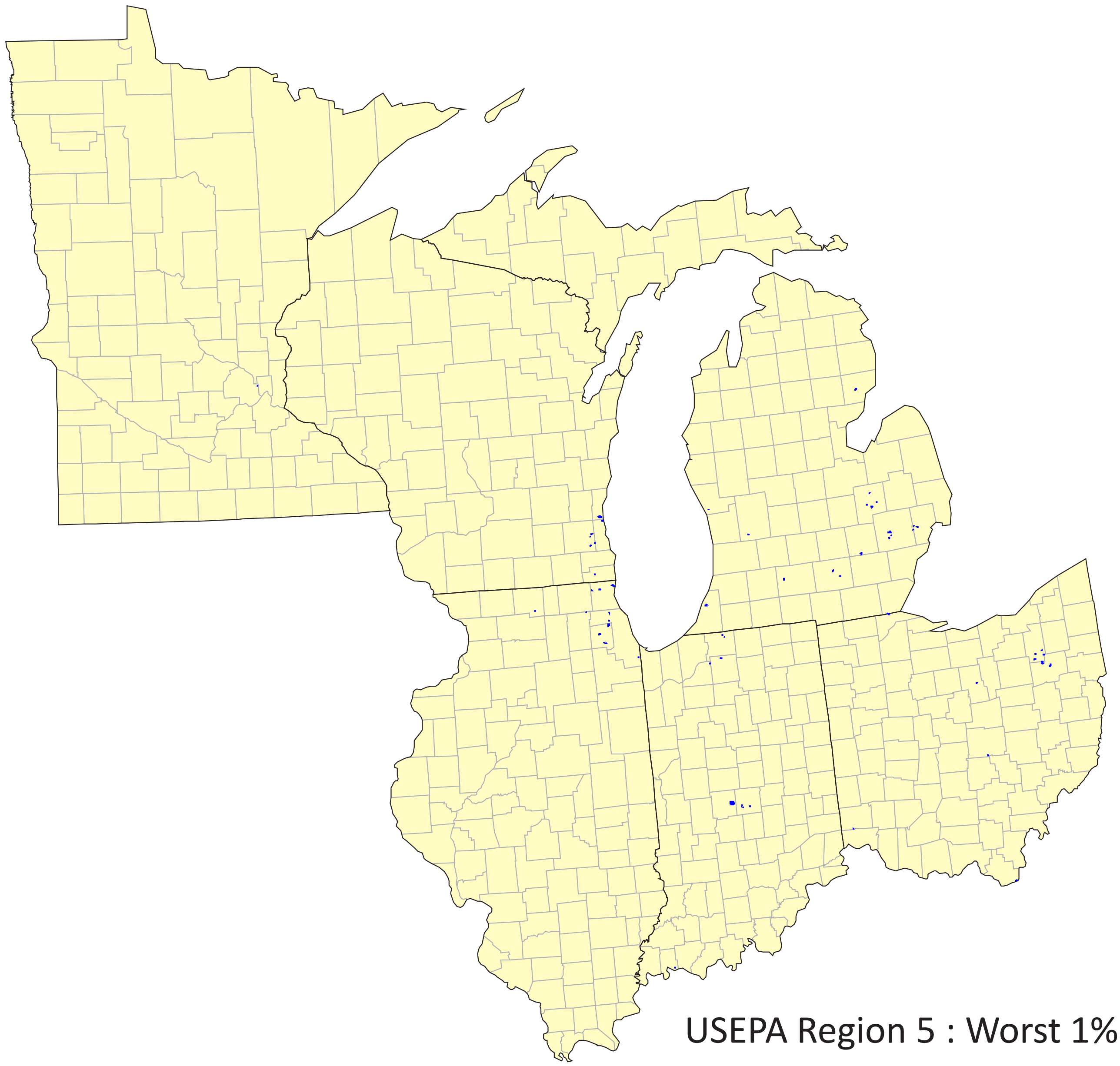


USEPA Region 5 : Worst 10%

Vulnerability Index 3: $\dfrac{\text{\# Service Stations} * \text{\# Households}}{\text{Surface Area}}$



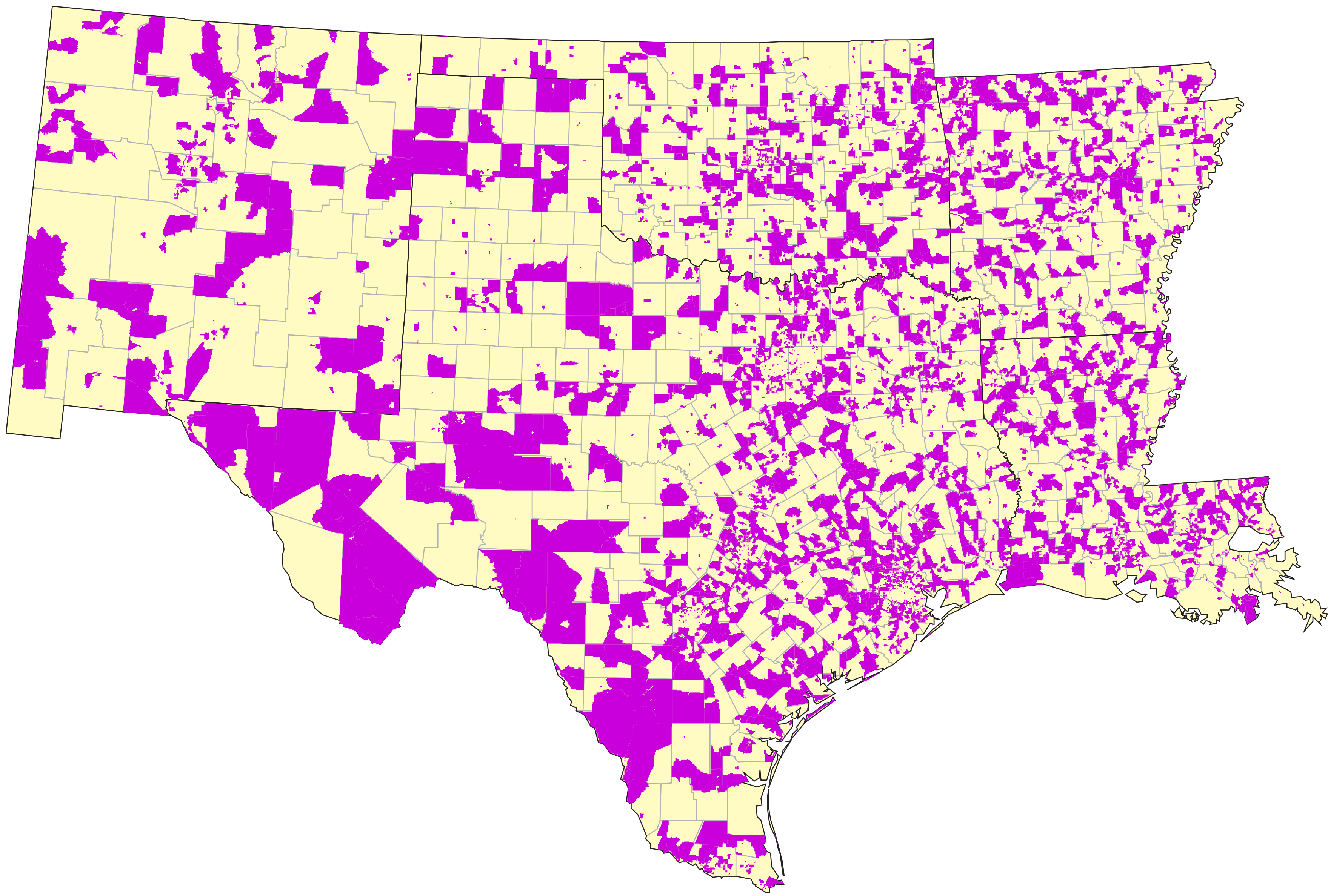
Vulnerability Index 3: $\dfrac{\#\ \text{Service Stations} * \#\ \text{Households}}{\text{Surface Area}}$



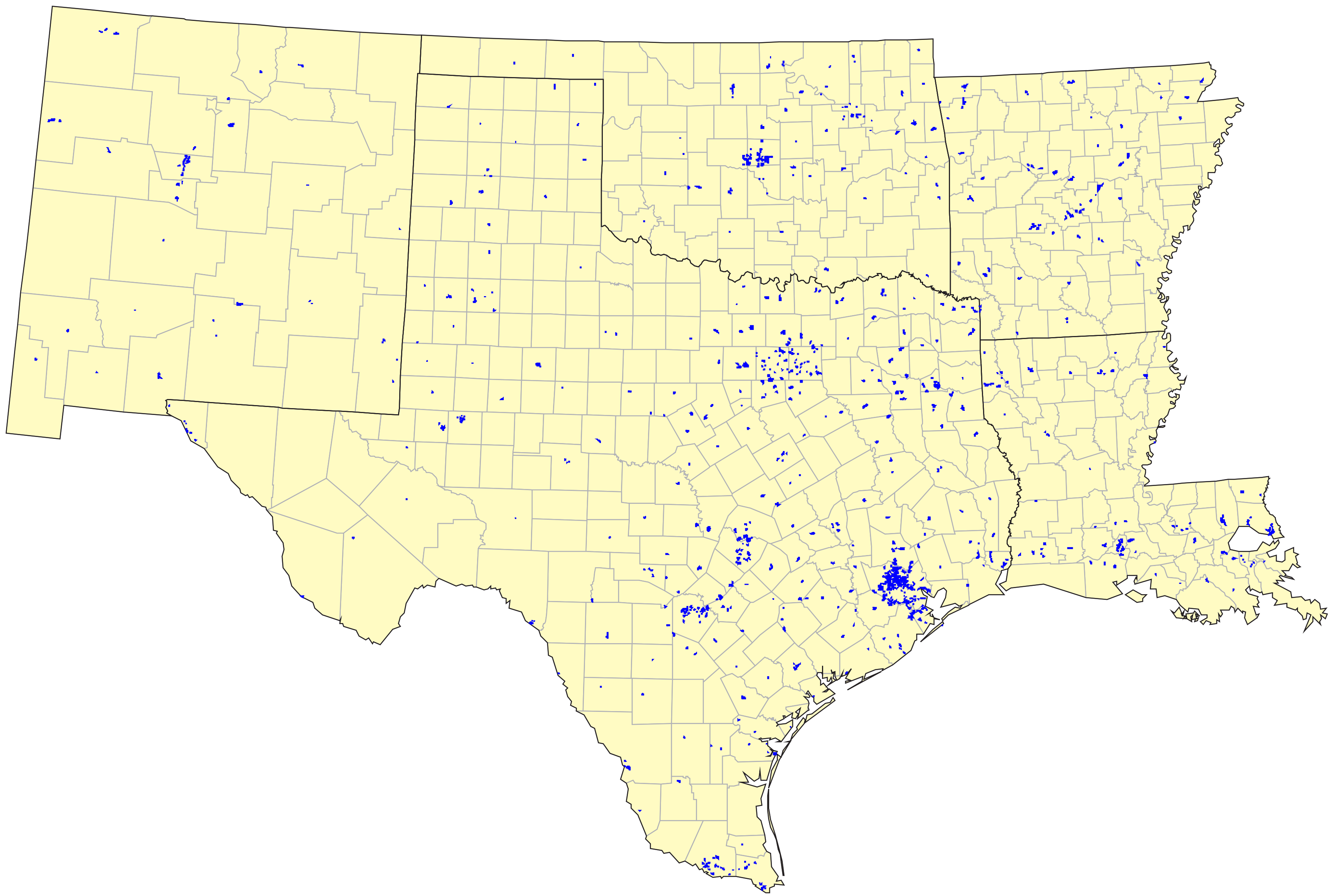
Vulnerability Index 3: $\frac{\#\ \text{Service Stations} \ * \ \#\ \text{Households}}{\text{Surface Area}}$

Appendix G

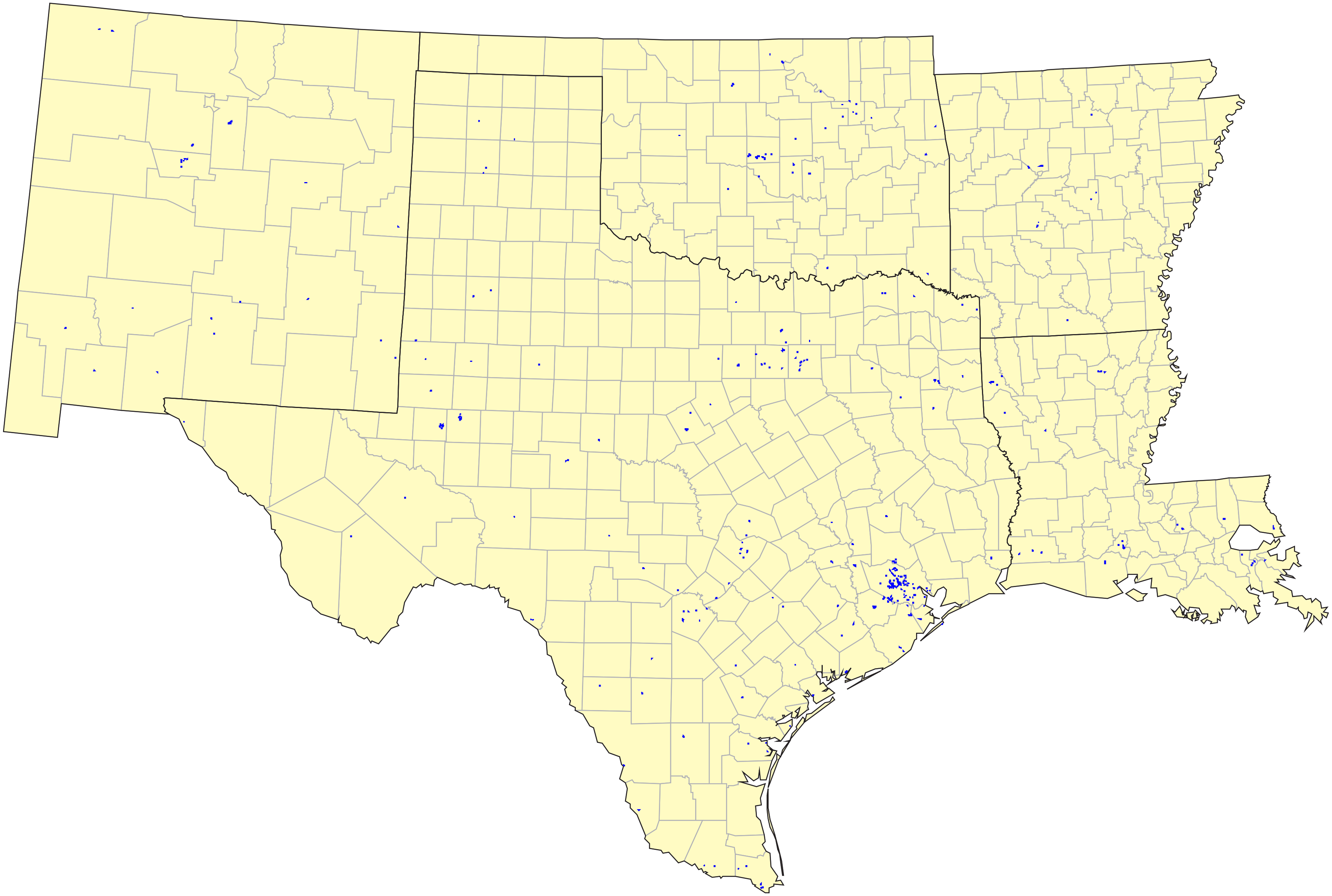
USEPA Region 6 Vulnerability



1990 US Census Blocks that contain BOTH Consumers
of Shallow Drinking Water and Service Stations

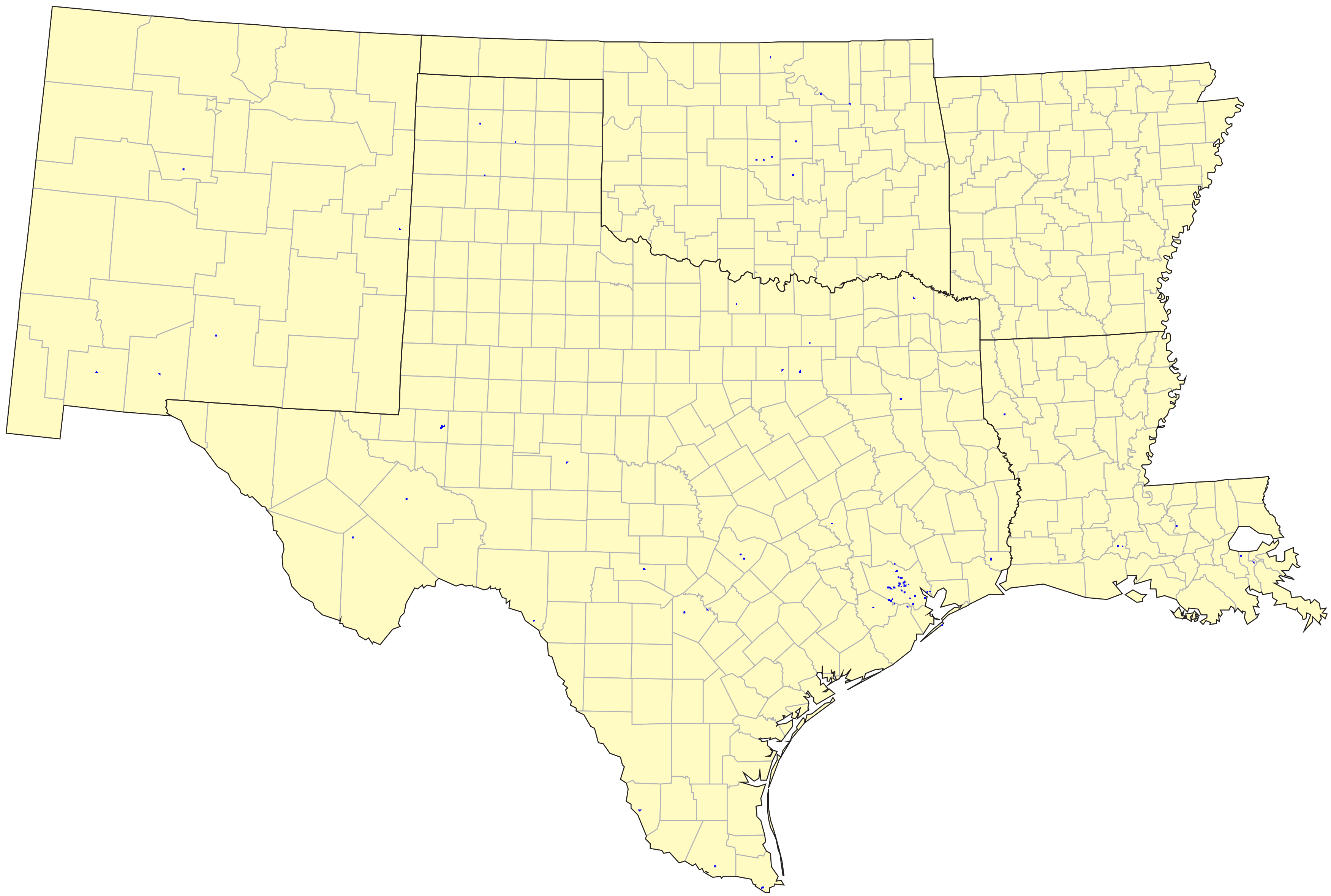


Vulnerability Index 1: Density of Service Stations (stations per square mile) USEPA Region 6 : Upper 30%

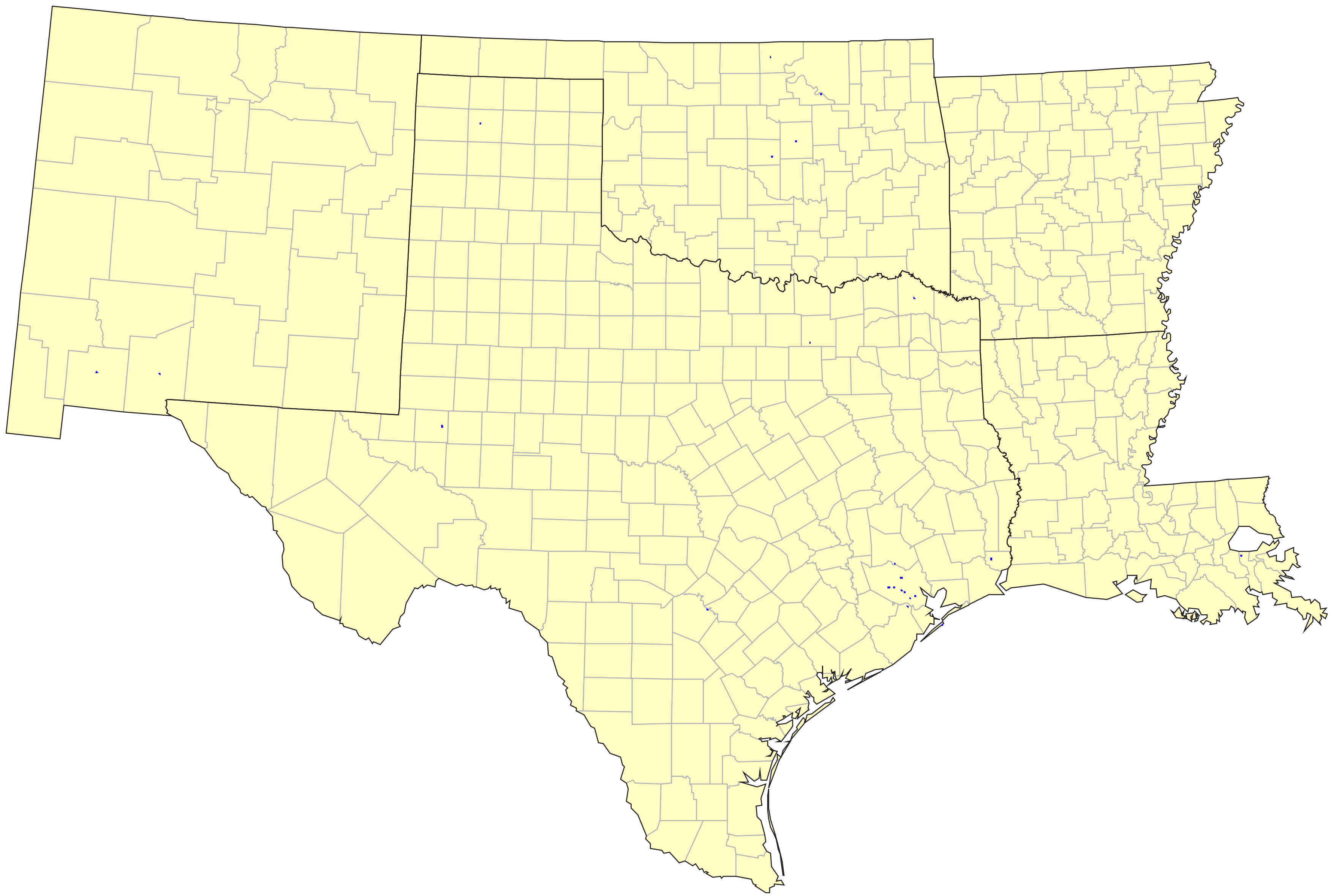


Vulnerability Index 1: Density of Service Stations (stations per square mile)

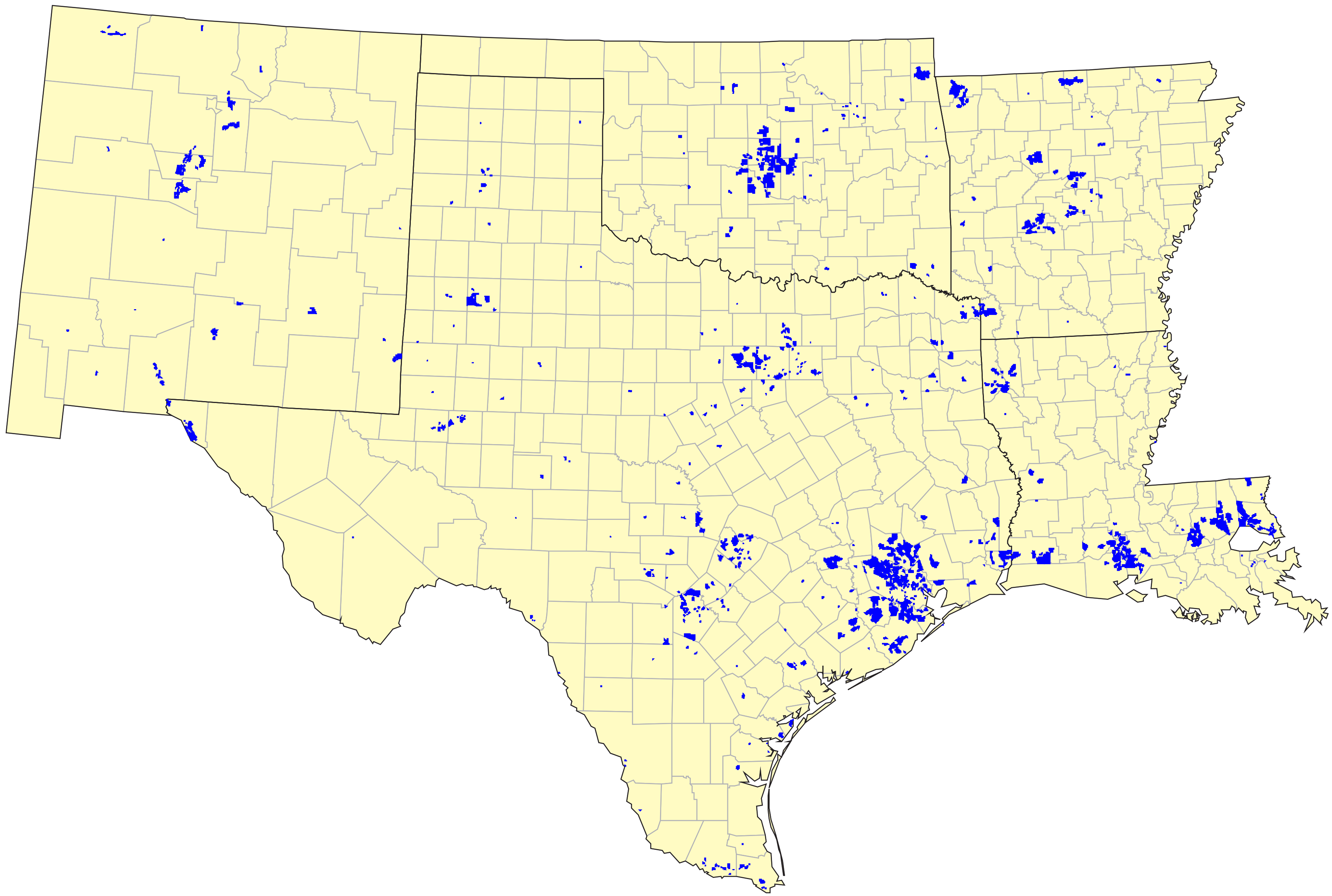
USEPA Region 6 : Upper 10%



Vulnerability Index 1: Density of Service Stations (stations per square mile) USEPA Region 6 : Upper 3%

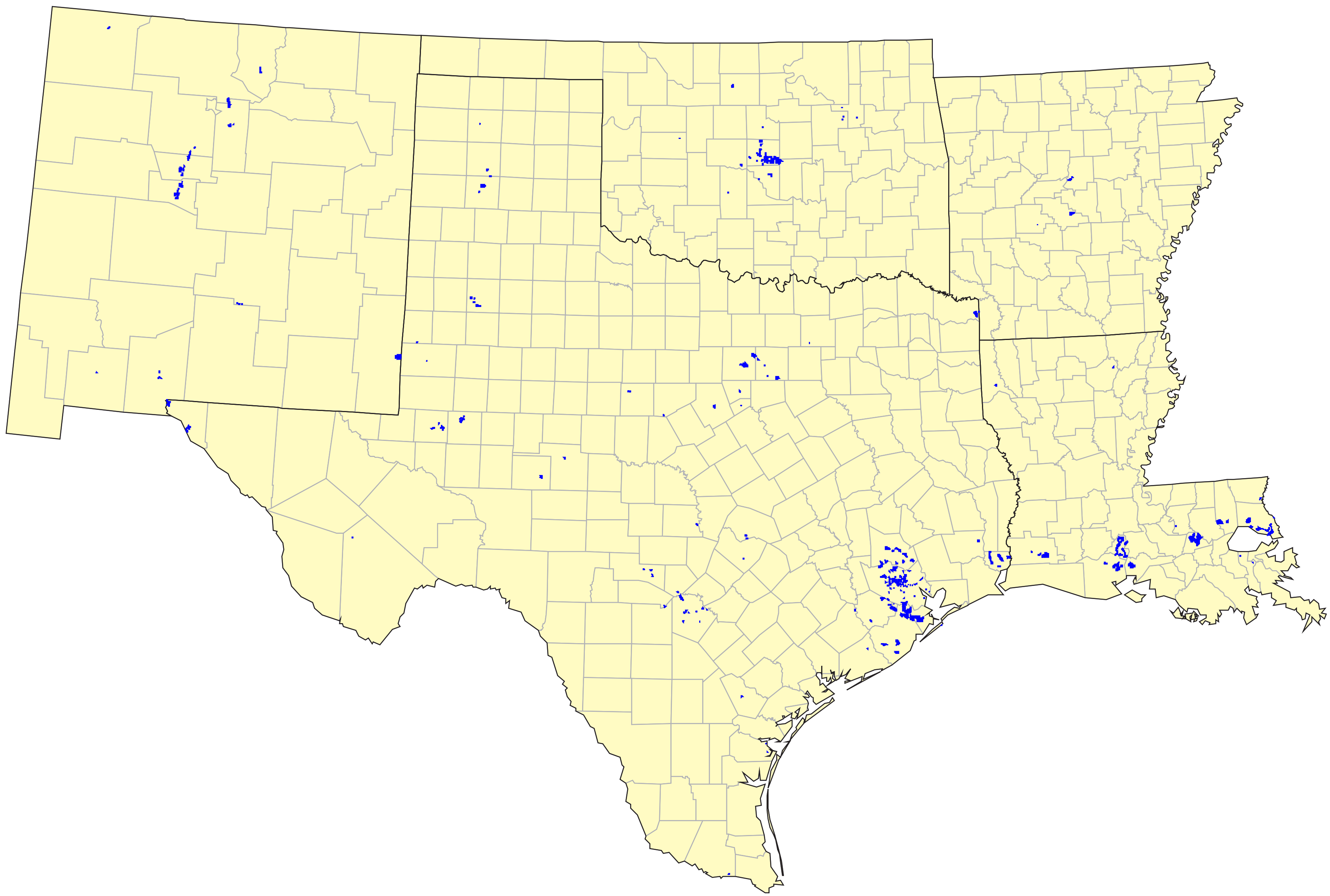


Vulnerability Index 1: Density of Service Stations (stations per square mile) USEPA Region 6 : Upper 1%



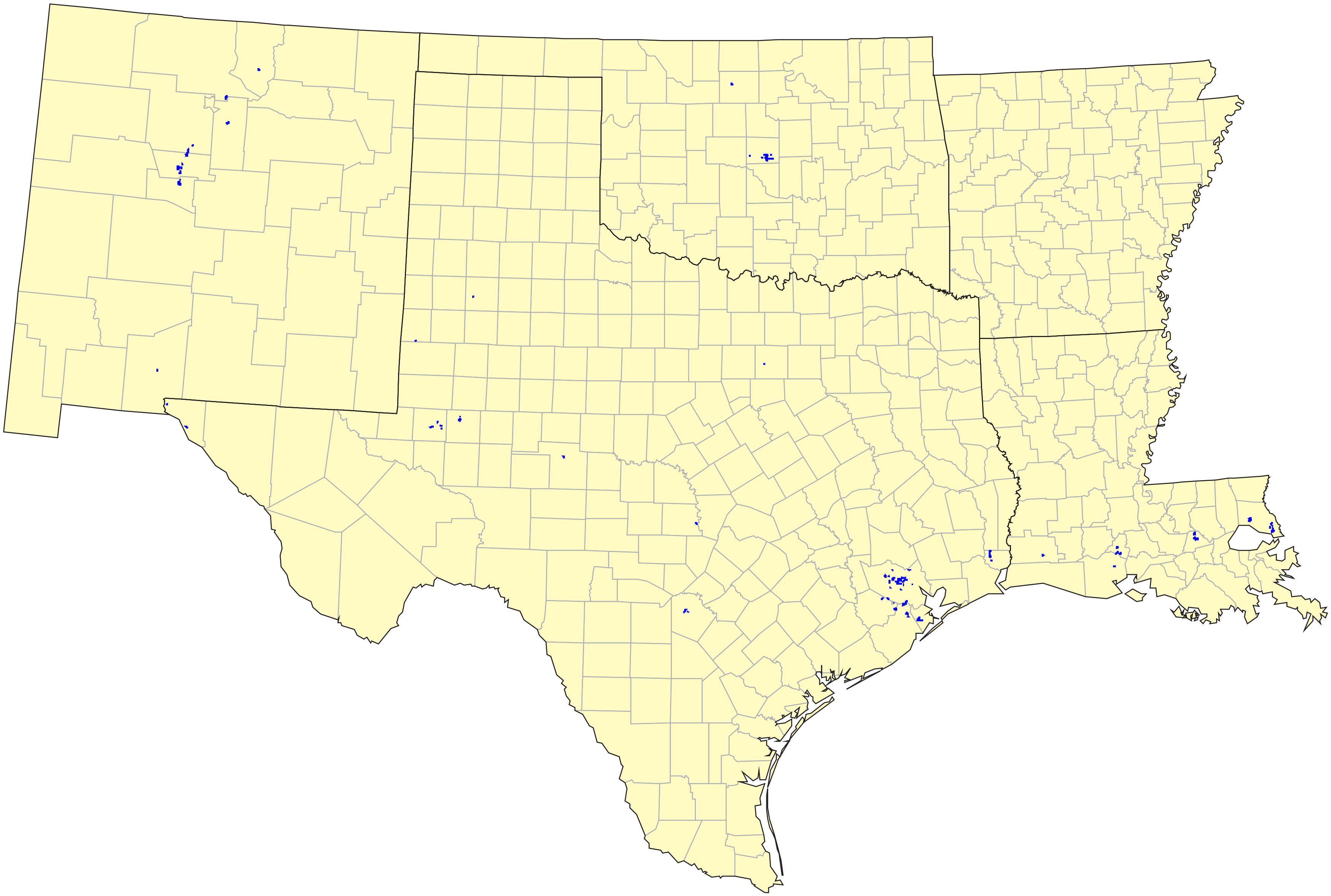
USEPA Region 6 : Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



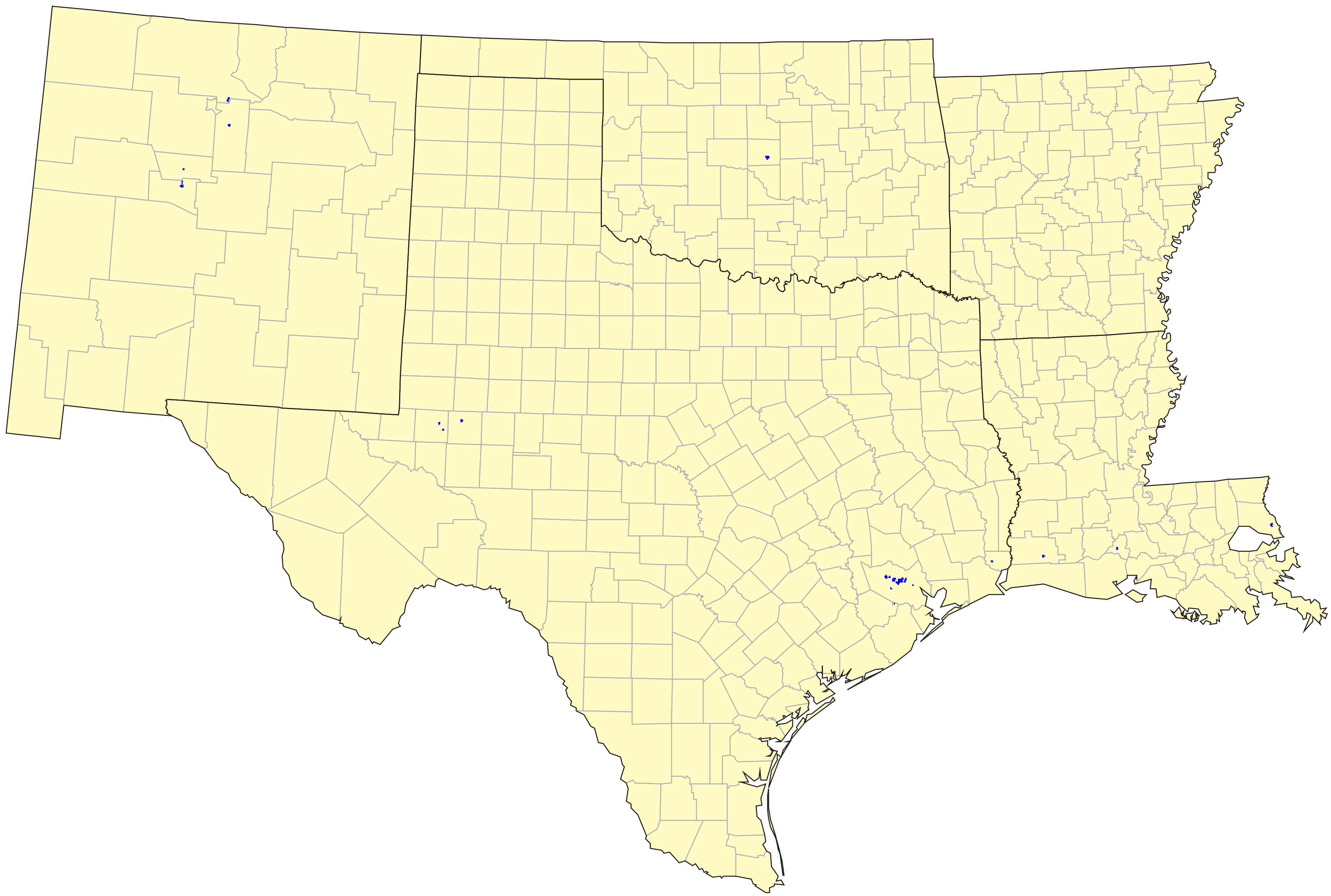
USEPA Region 6 : Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source
(households per square mile)



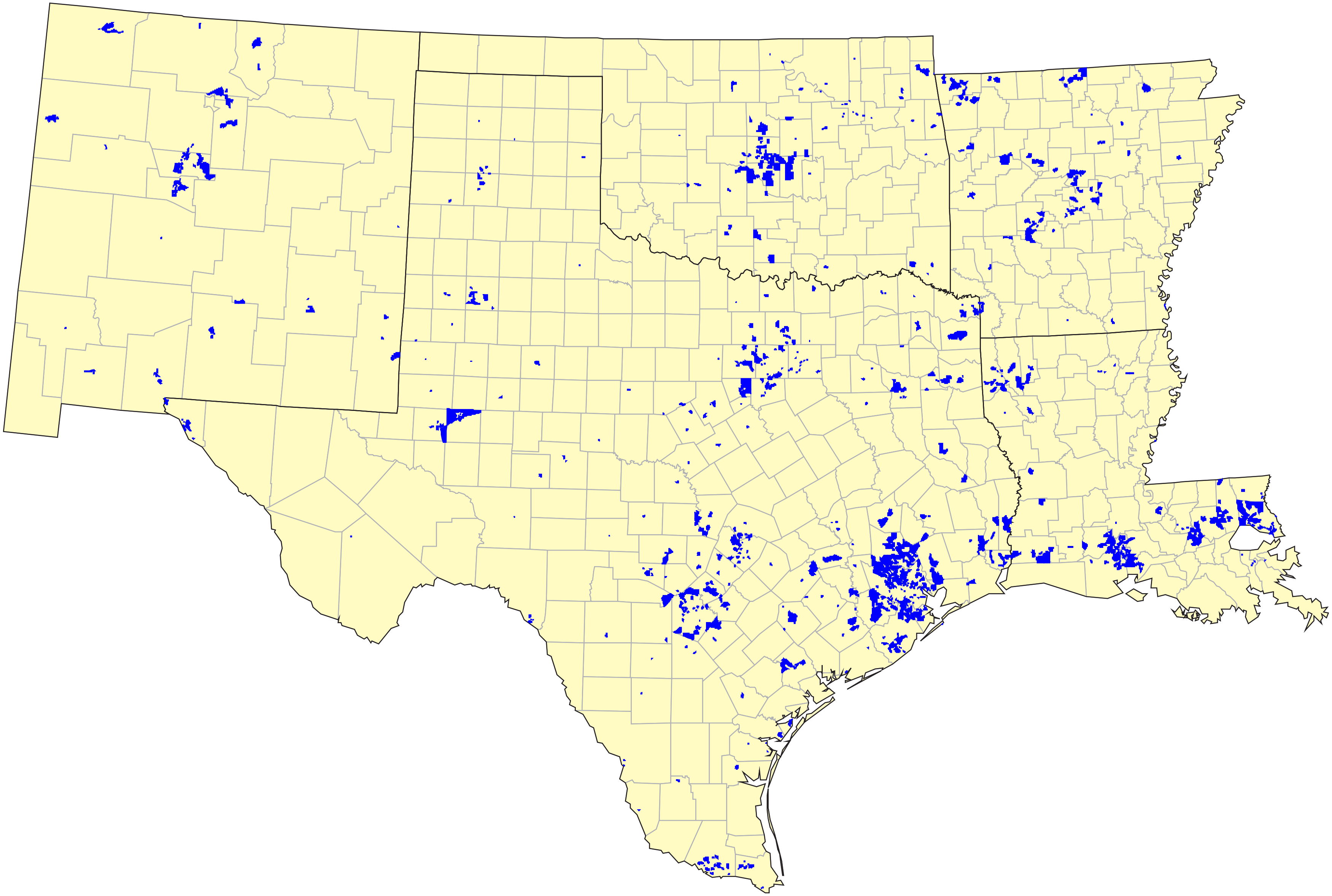
USEPA Region 6 : Upper 3%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

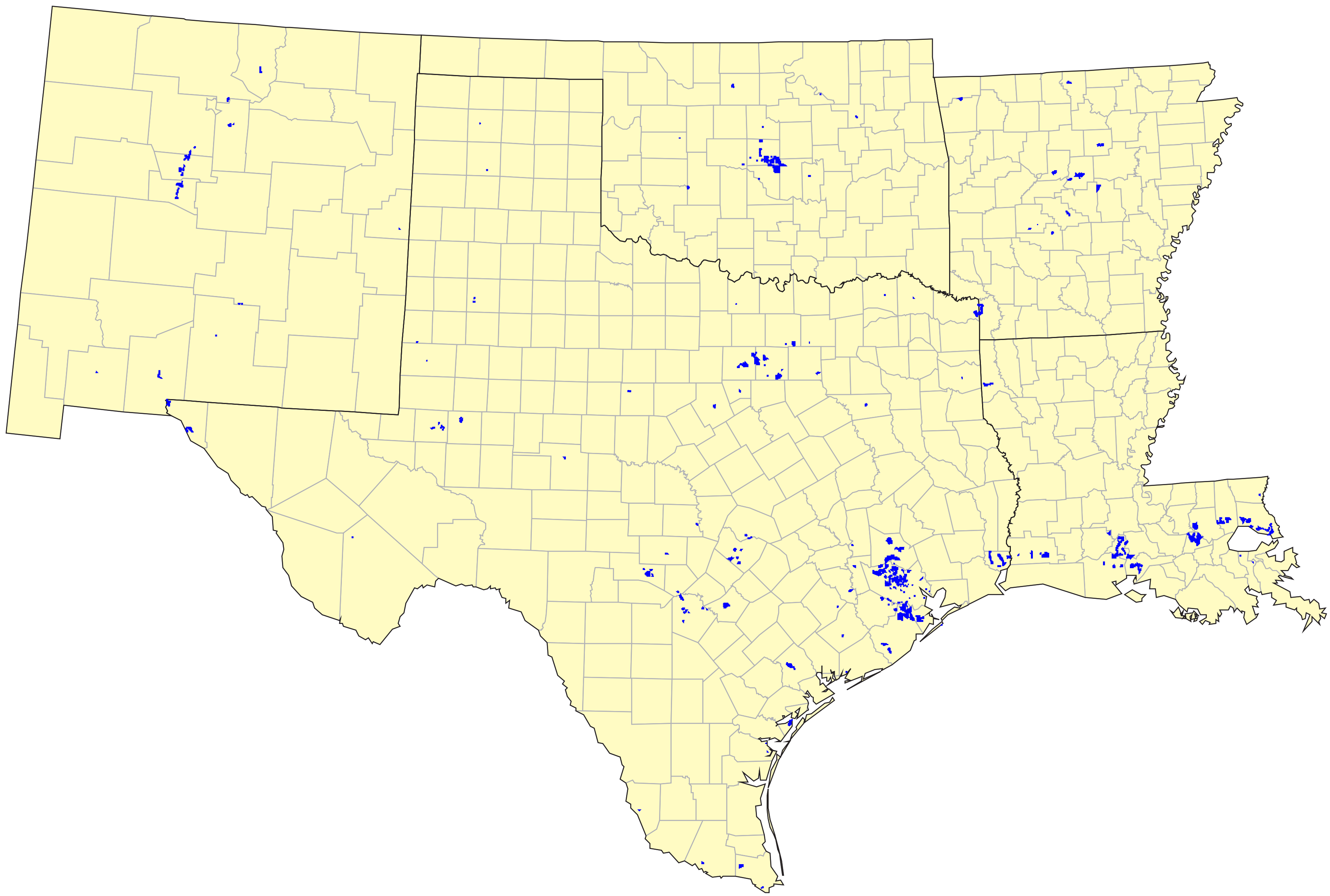


USEPA Region 6 : Upper 1%

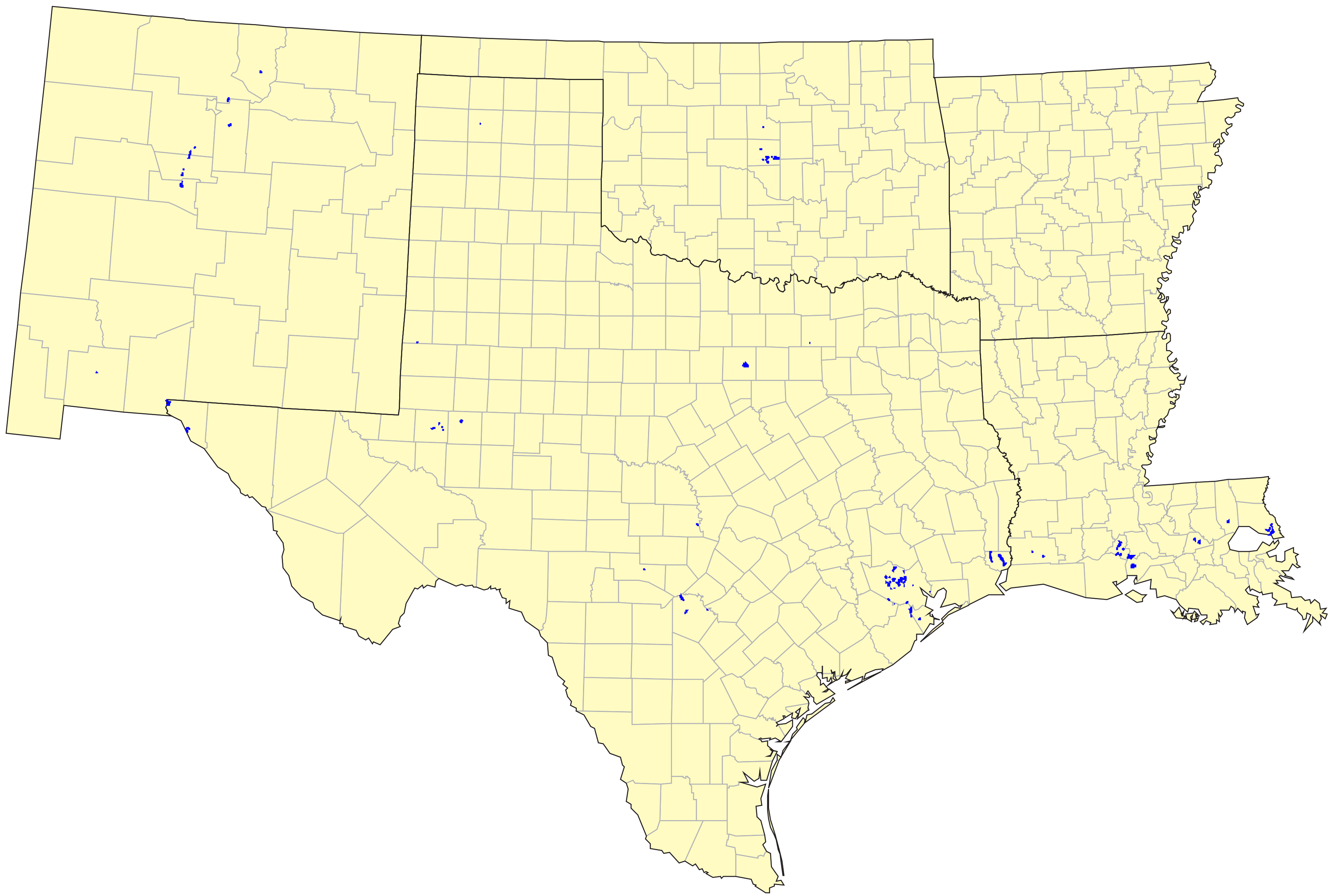
Vulnerability Index 2: Density of Households using Water from a Private Source
(households per square mile)



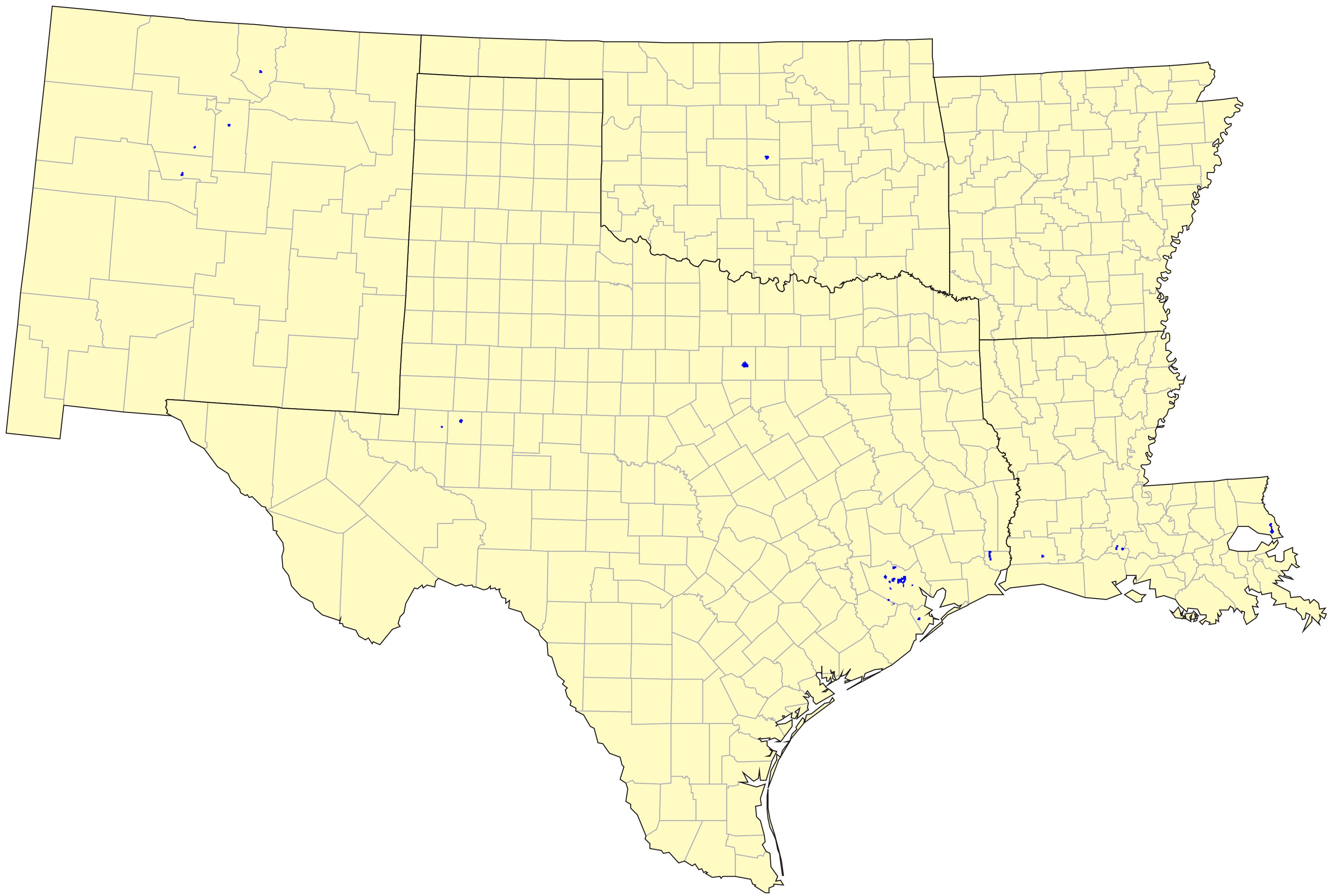
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 6 : Upper 30%



Vulnerability Index 3: $\dfrac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 6 : Upper 10%



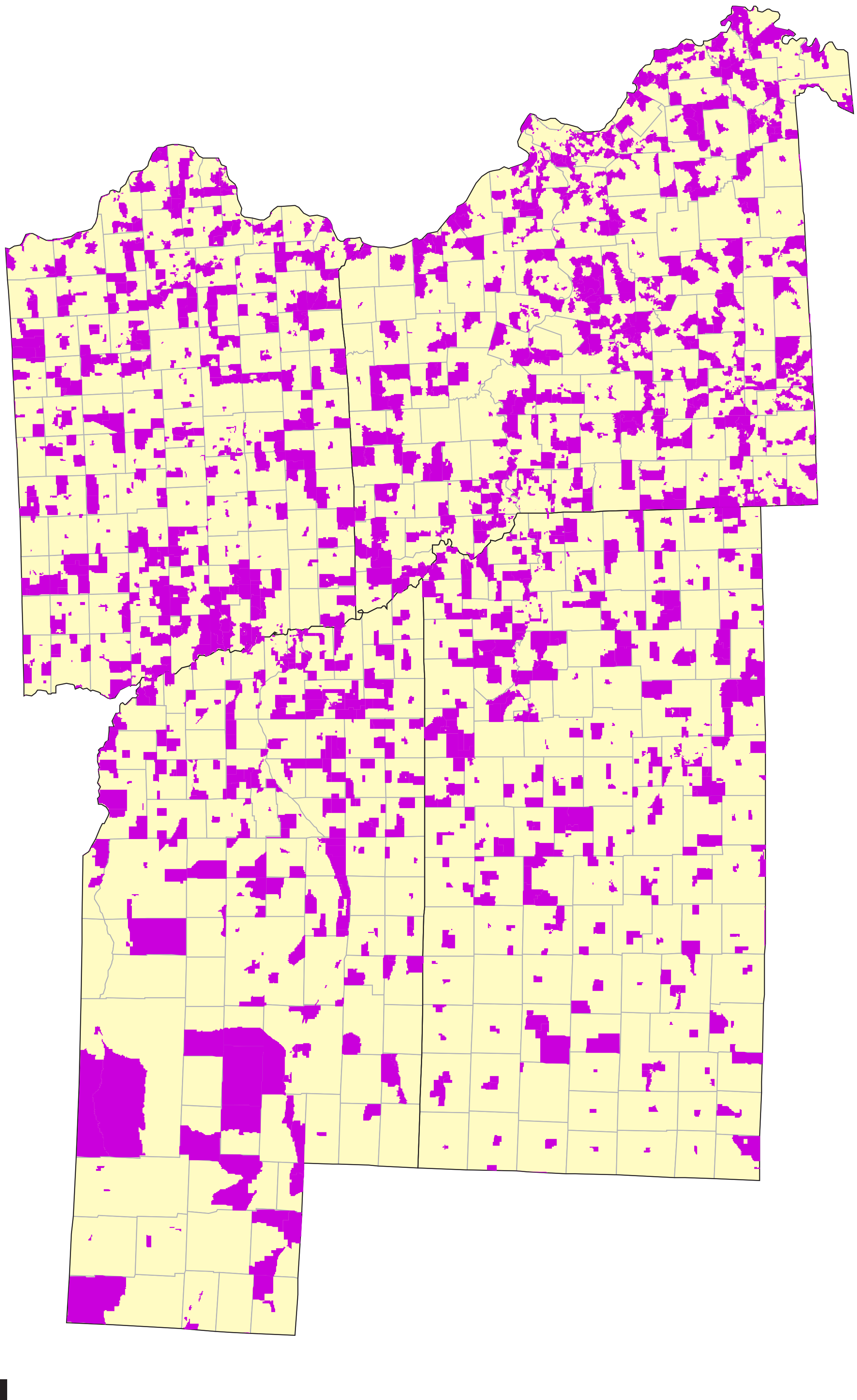
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 6 : Upper 3%



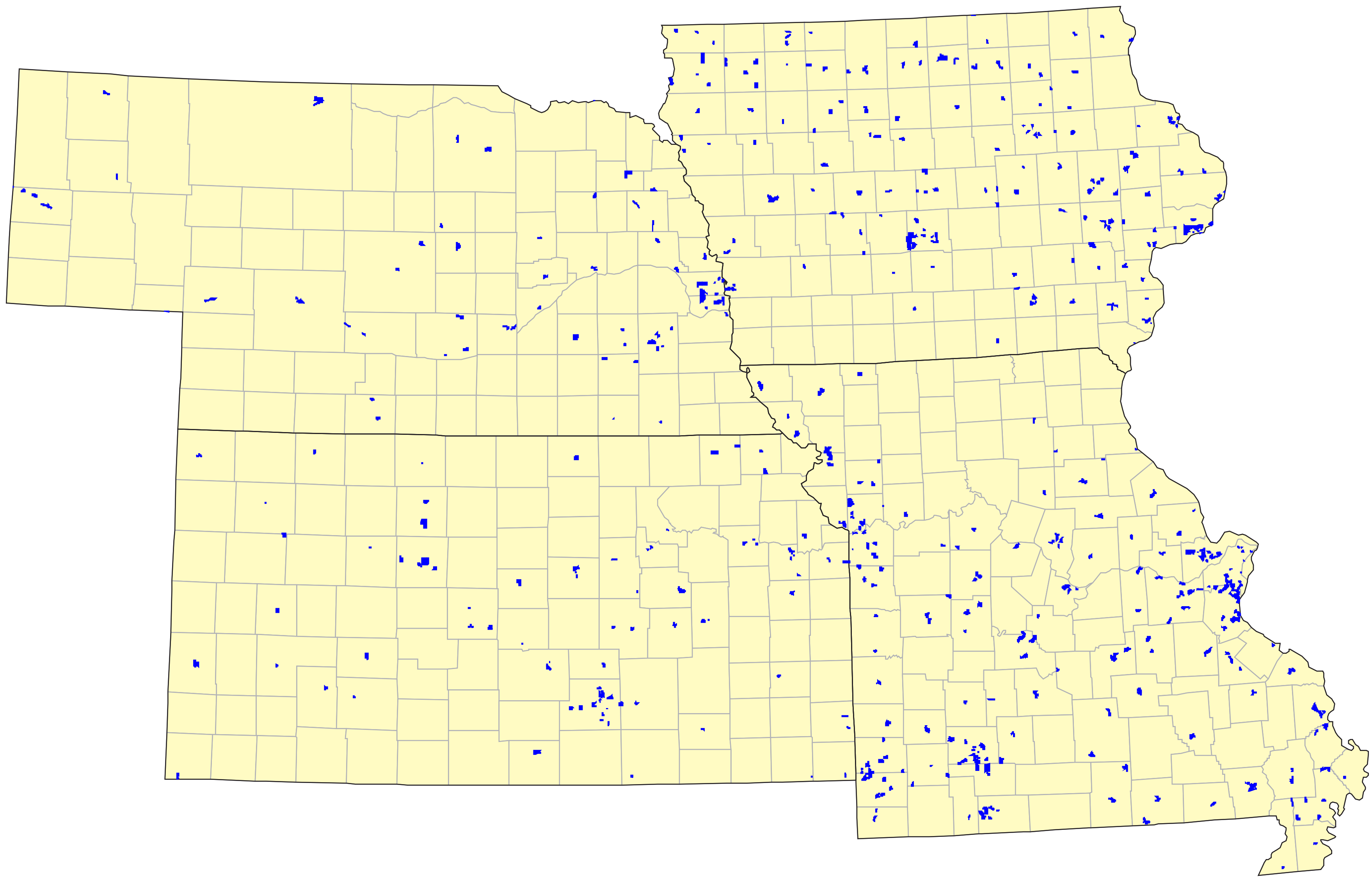
Vulnerability Index 3: $\frac{\#\ \text{Service Stations} * \#\ \text{Households}}{\text{Surface Area}}$ USEPA Region 6 : Upper 1%

Appendix H

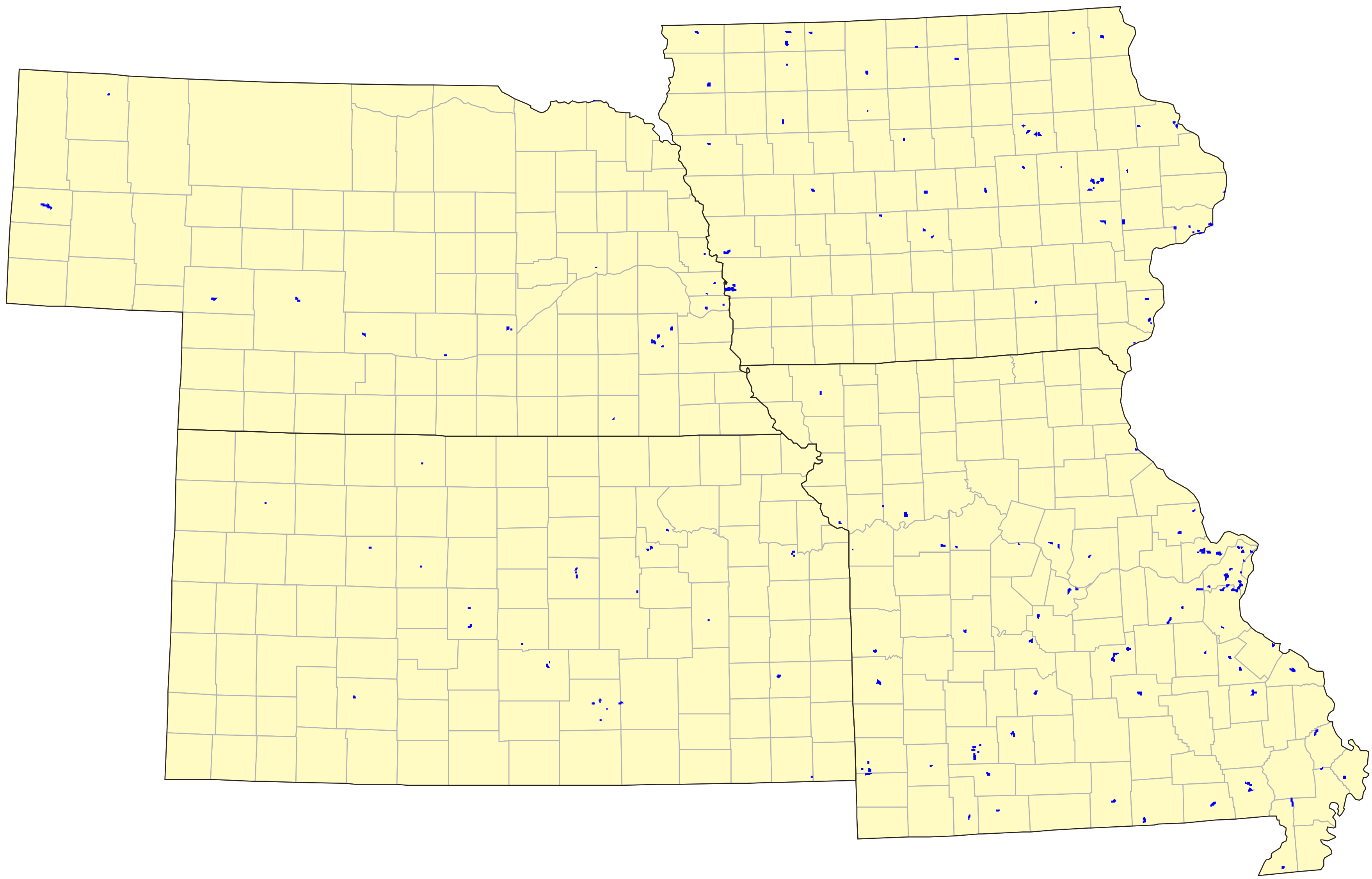
USEPA Region 7 Vulnerability



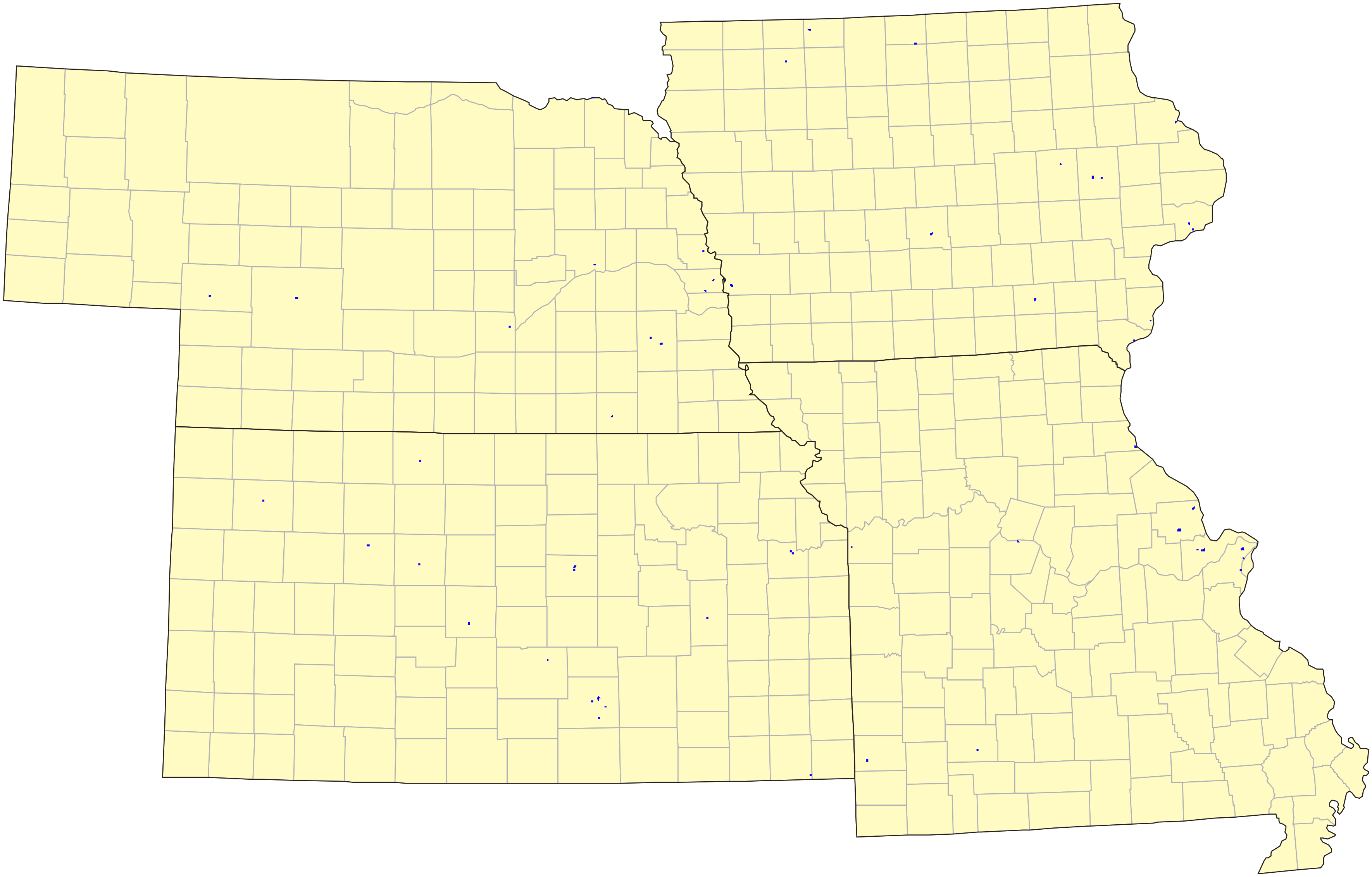
1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations



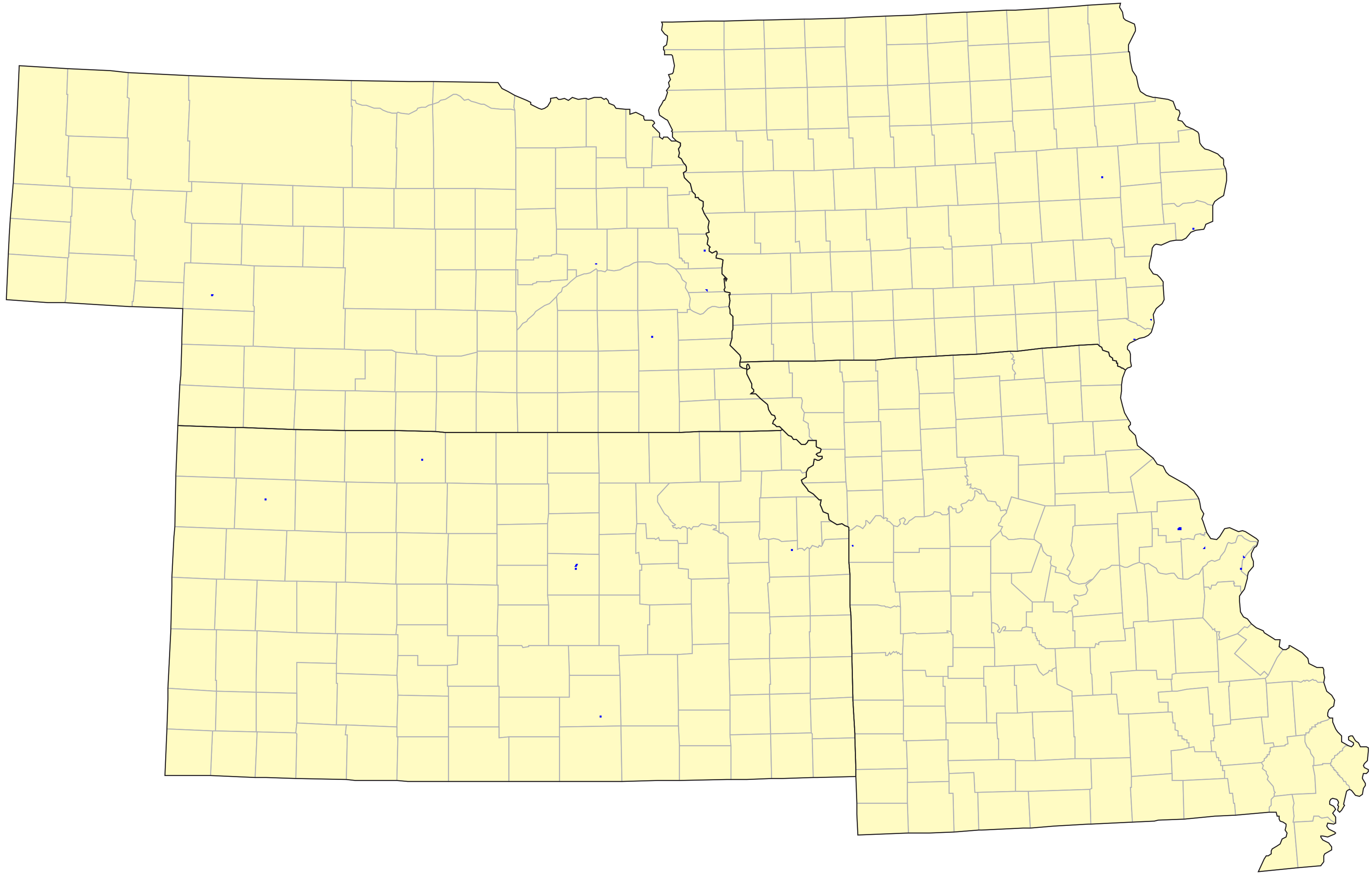
Vulnerability Index 1: Density of Service Stations (stations per square mile) USEPA Region 7 : Upper 30%



Vulnerability Index 1: Density of Service Stations (stations per square mile) USEPA Region 7 : Upper 10%

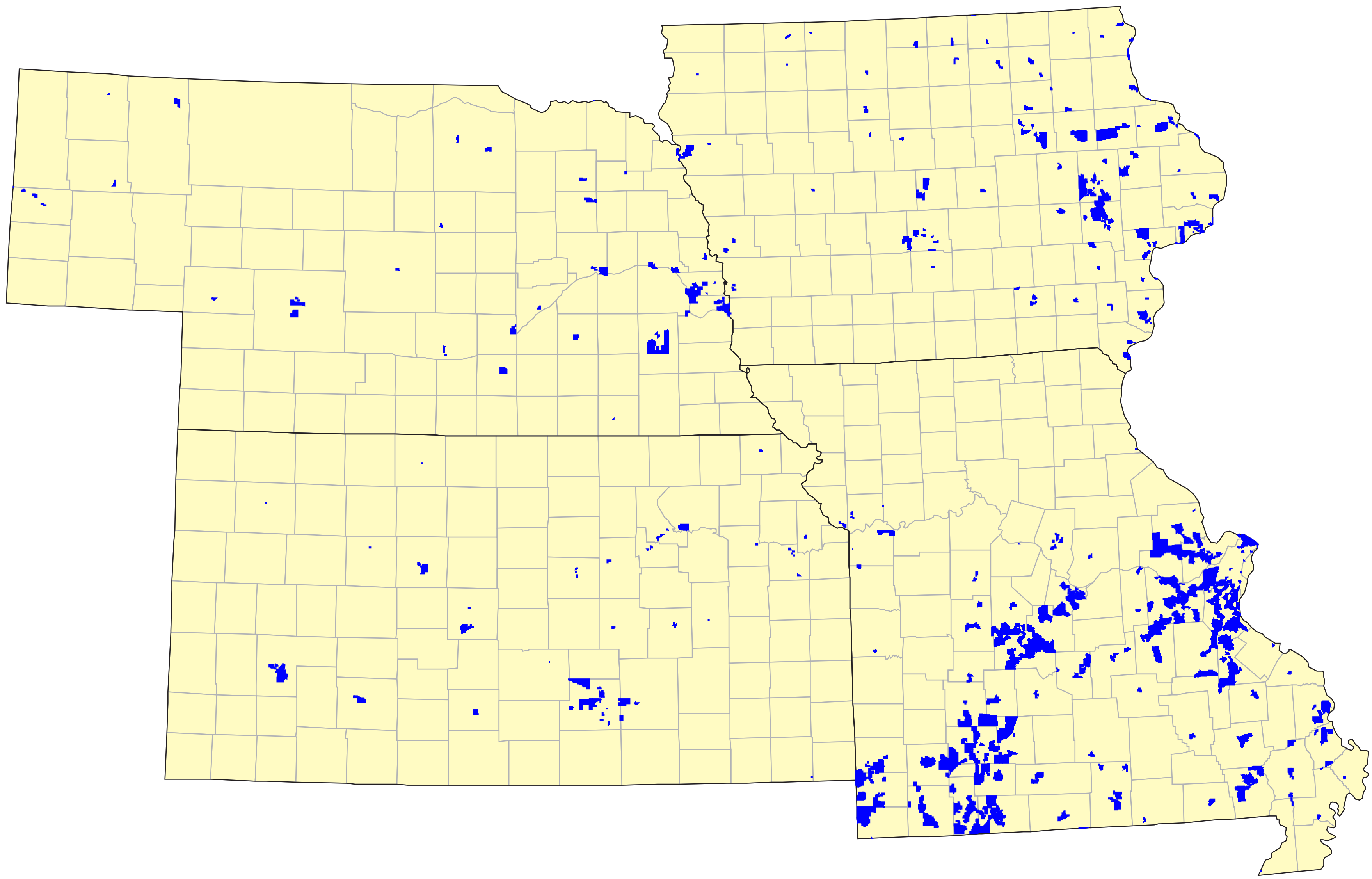


Vulnerability Index 1: Density of Service Stations (stations per square mile) USEPA Region 7 : Upper 3%



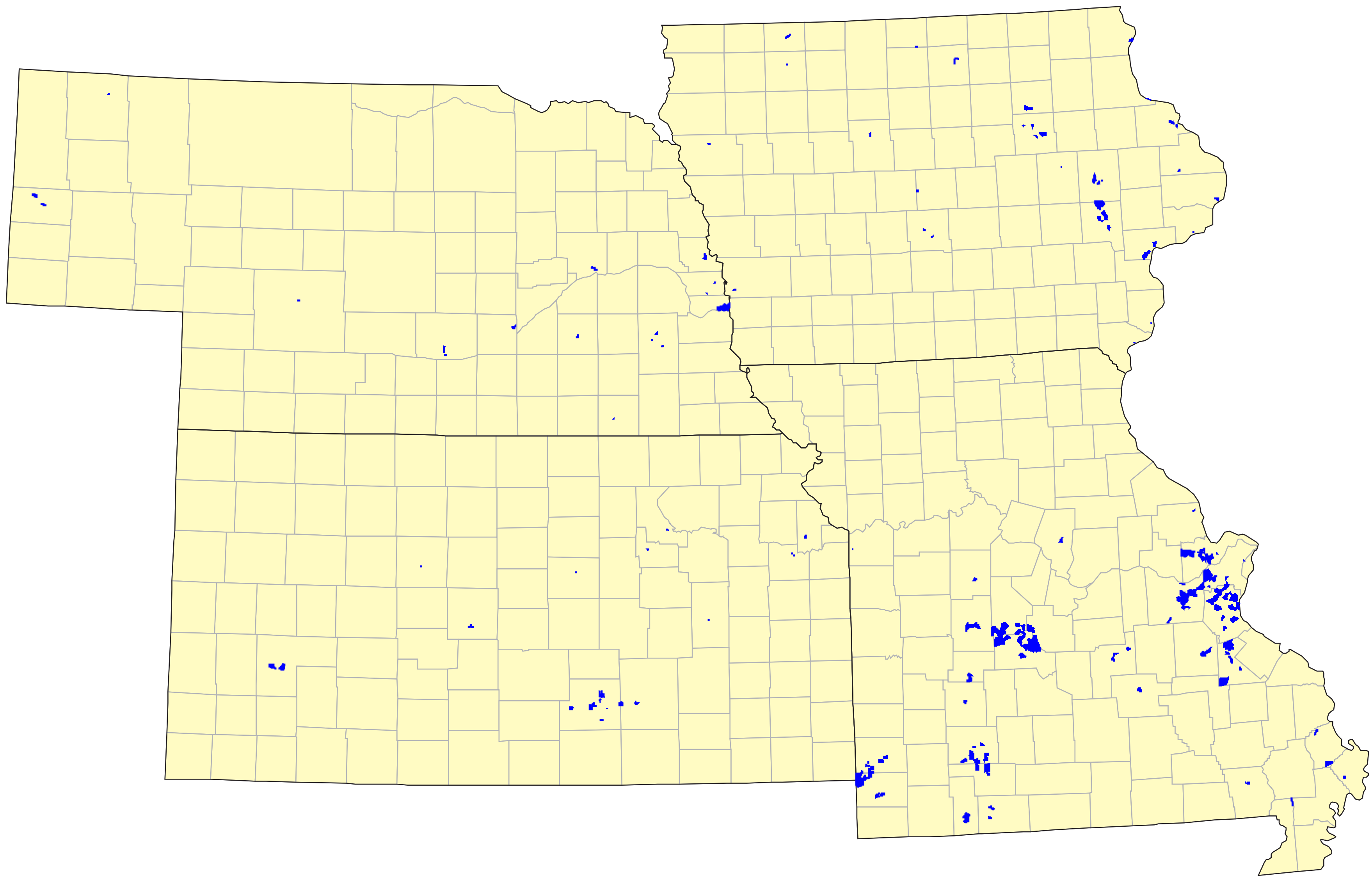
Vulnerability Index 1: Density of Service Stations (stations per square mile)

USEPA Region 7 : Upper 1%



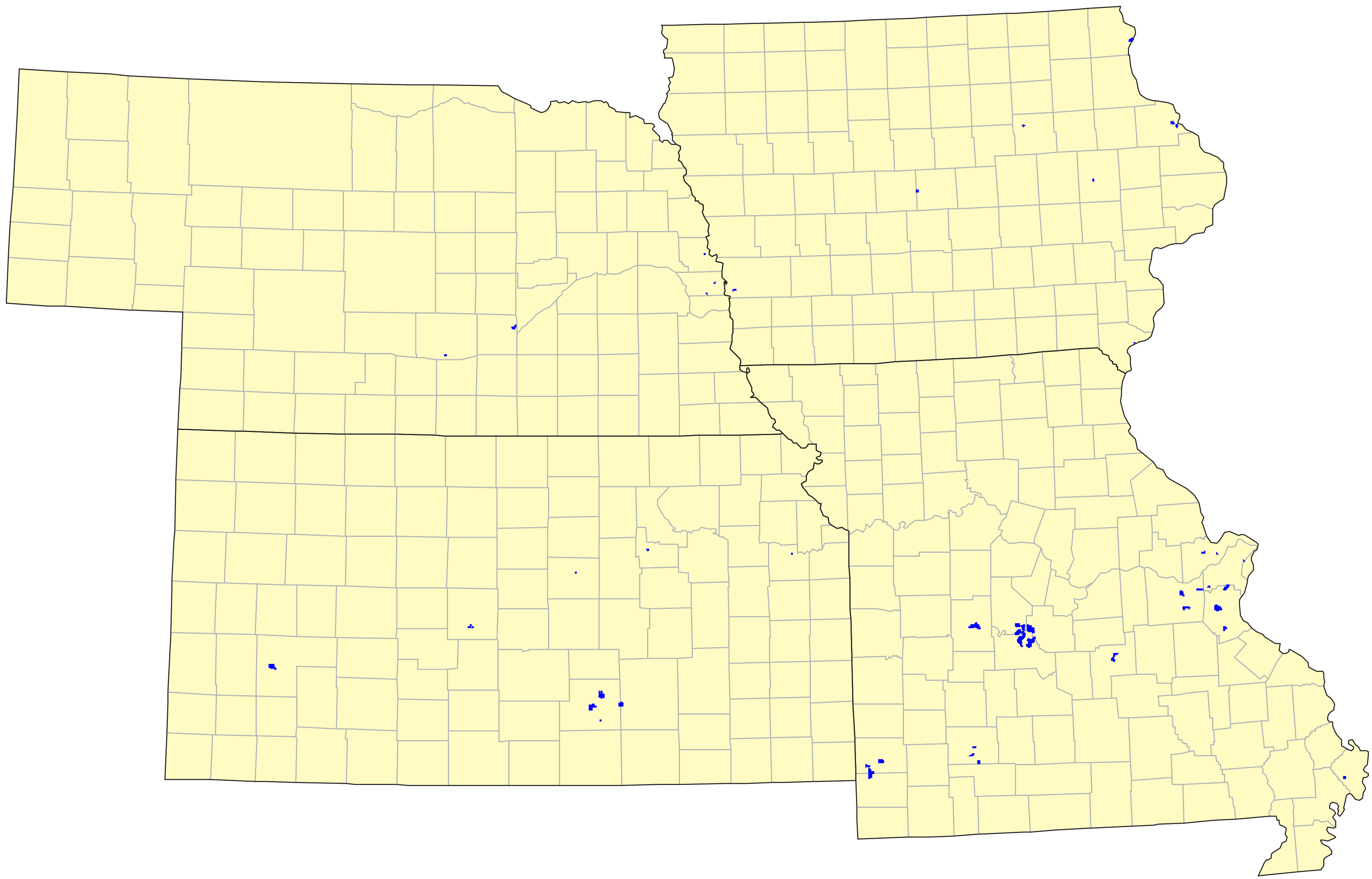
USEPA Region 7 : Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source
(households per square mile)



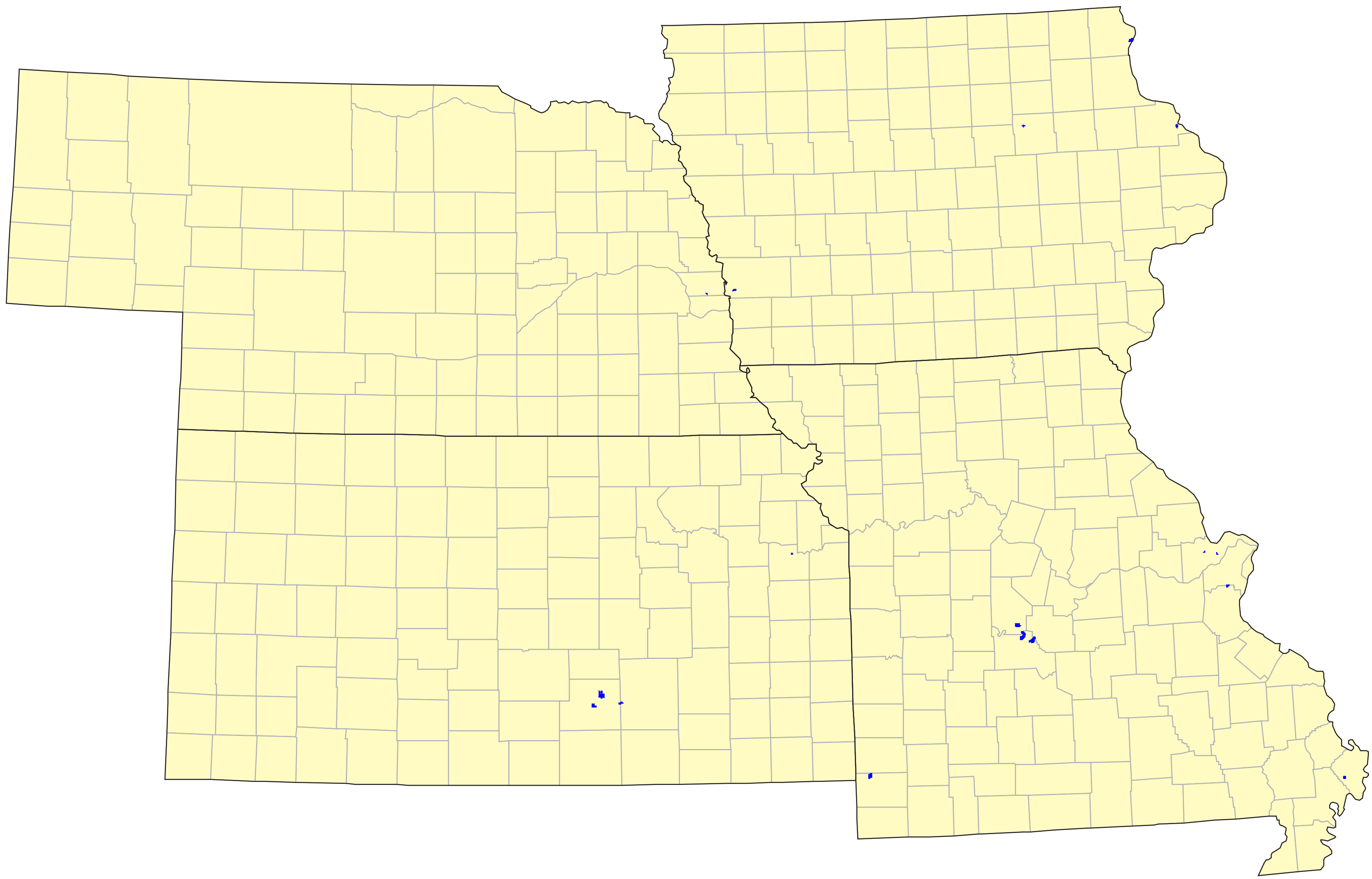
USEPA Region 7 : Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source
(households per square mile)



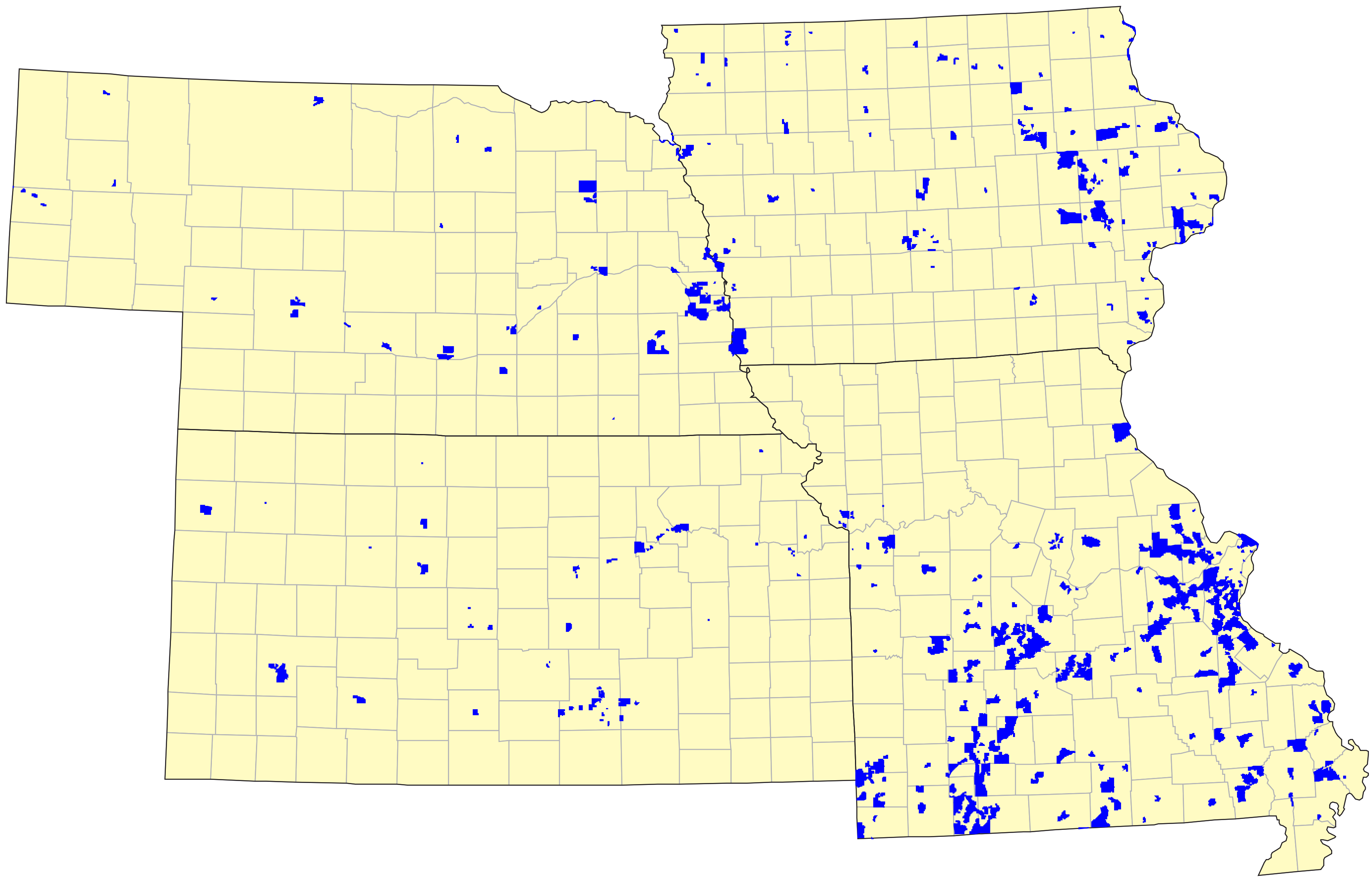
USEPA Region 7 : Upper 3%

Vulnerability Index 2: Density of Households using Water from a Private Source
(households per square mile)

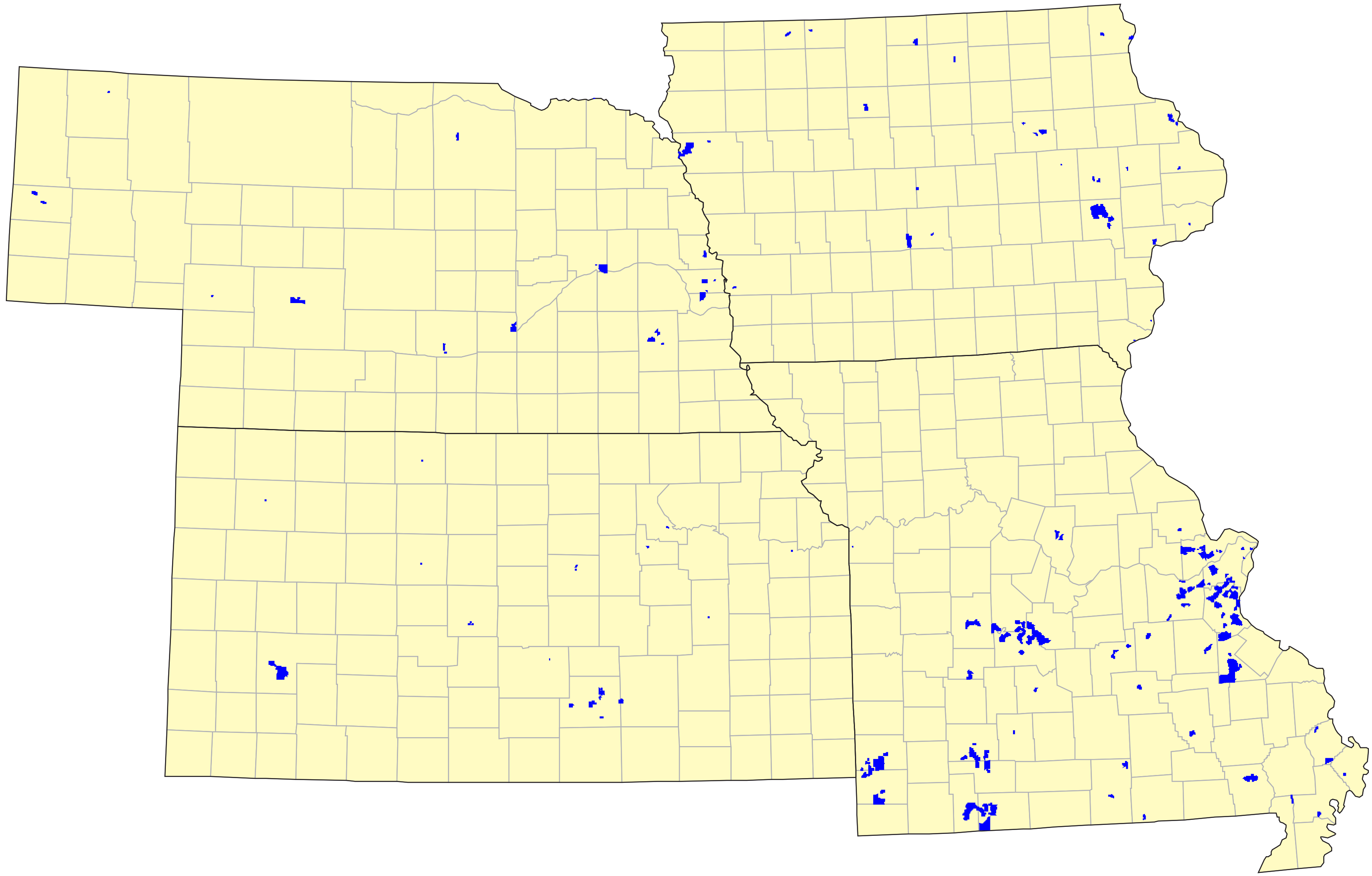


USEPA Region 7 : Upper 1%

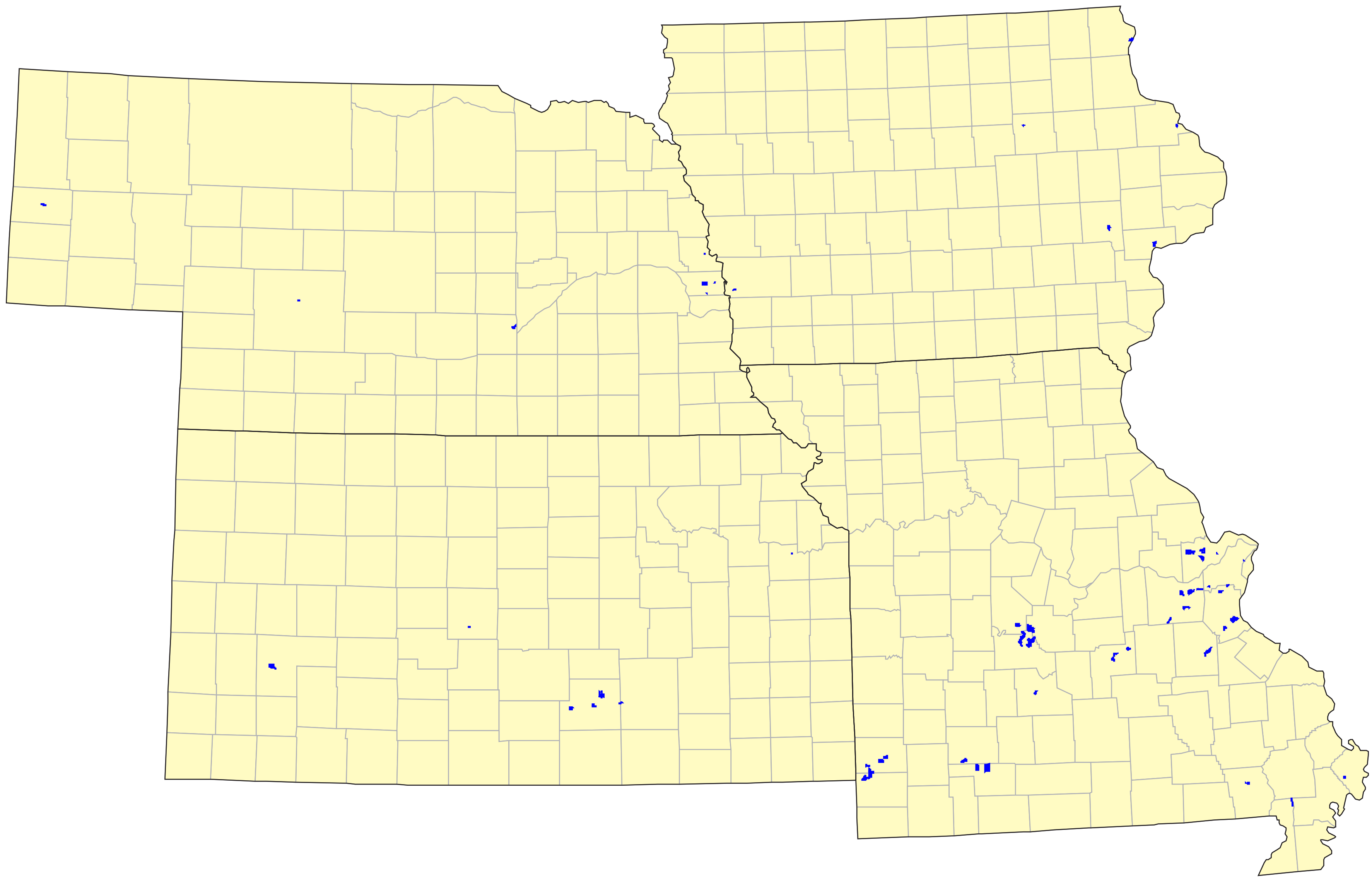
Vulnerability Index 2: Density of Households using Water from a Private Source
(households per square mile)



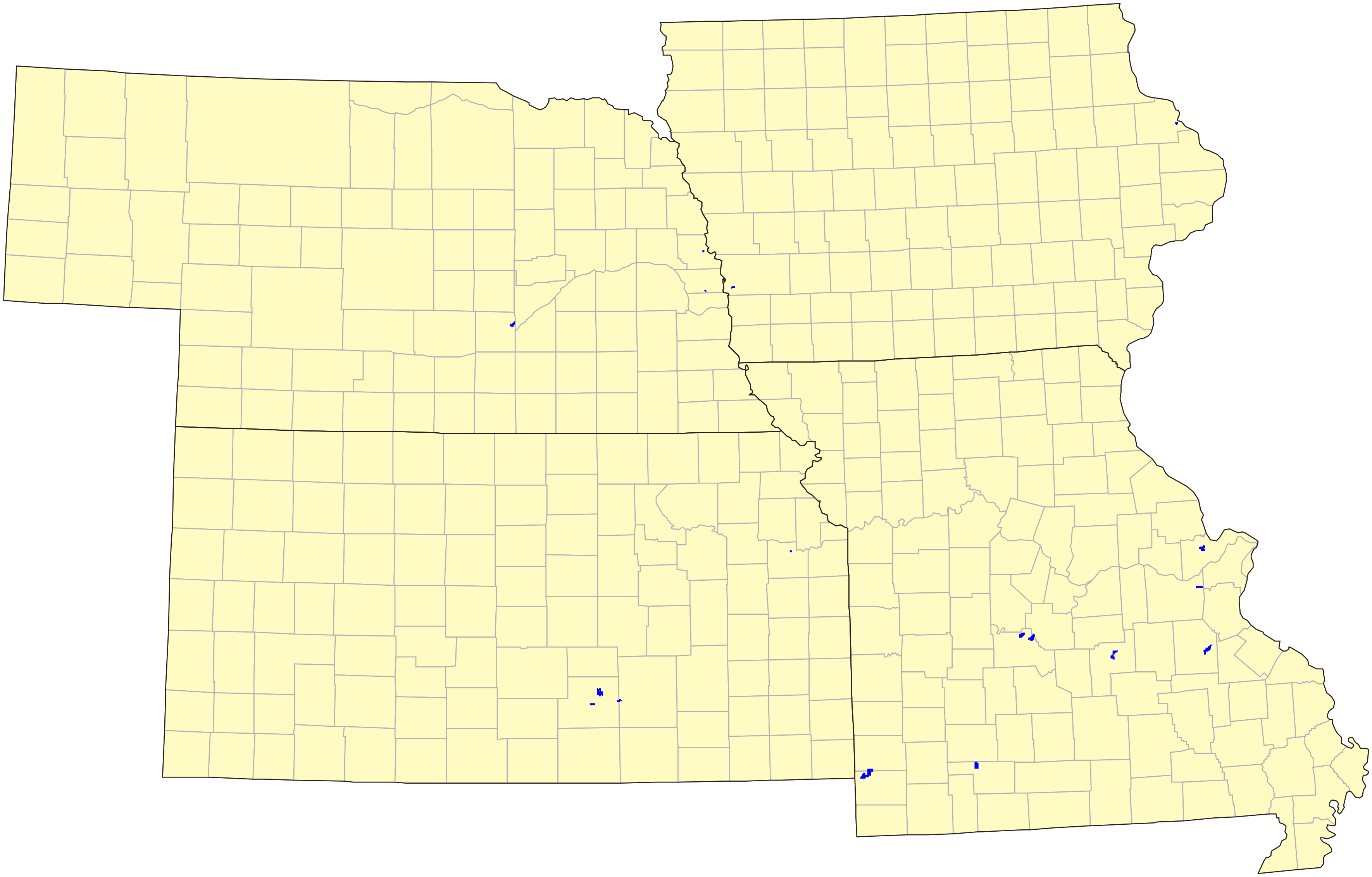
Vulnerability Index 3: $\dfrac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 7 : Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 7 : Upper 10%



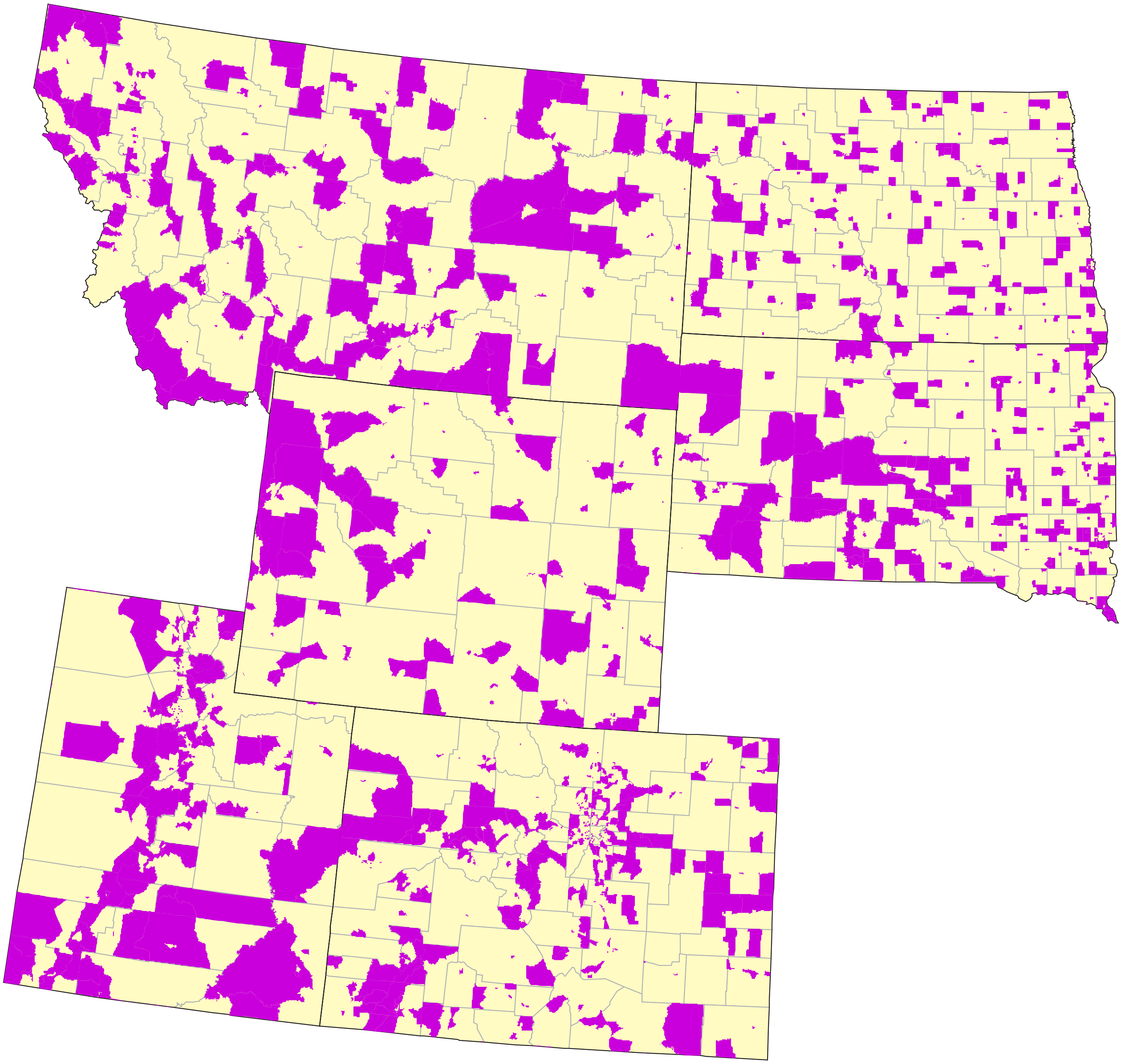
Vulnerability Index 3: $\dfrac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 7 : Upper 3%



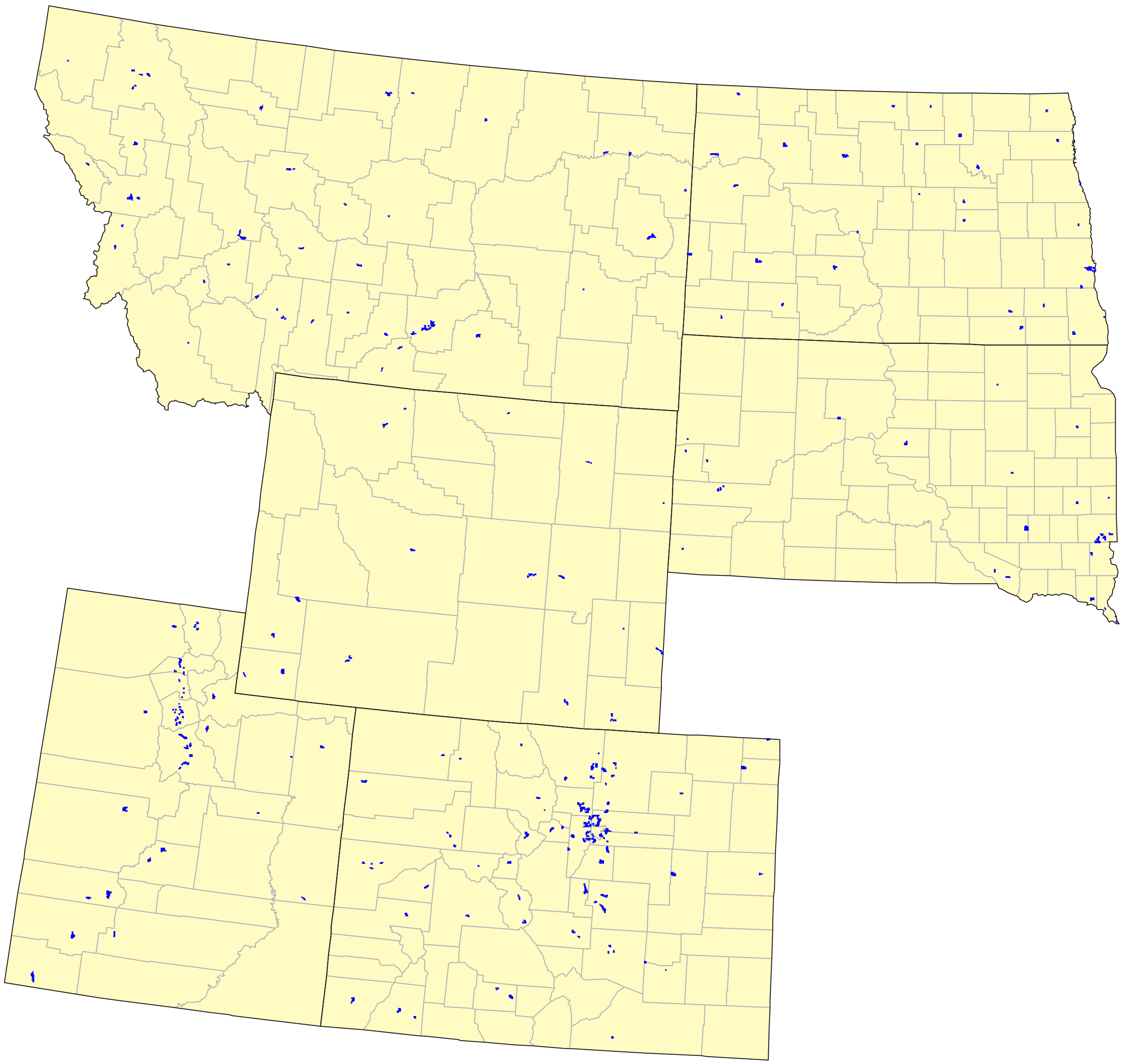
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 7 : Upper 1%

Appendix I

USEPA Region 8 Vulnerability

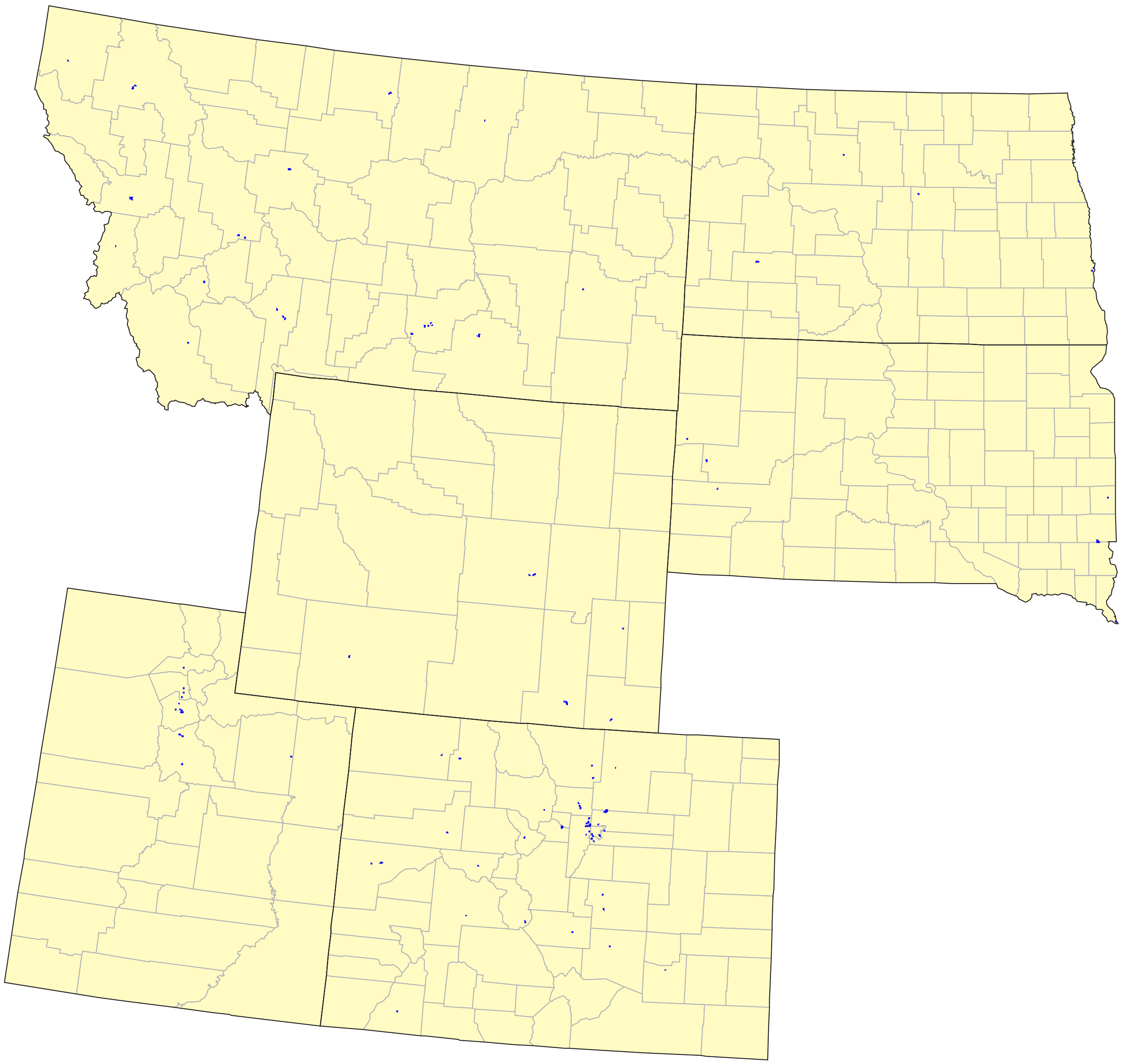


1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations



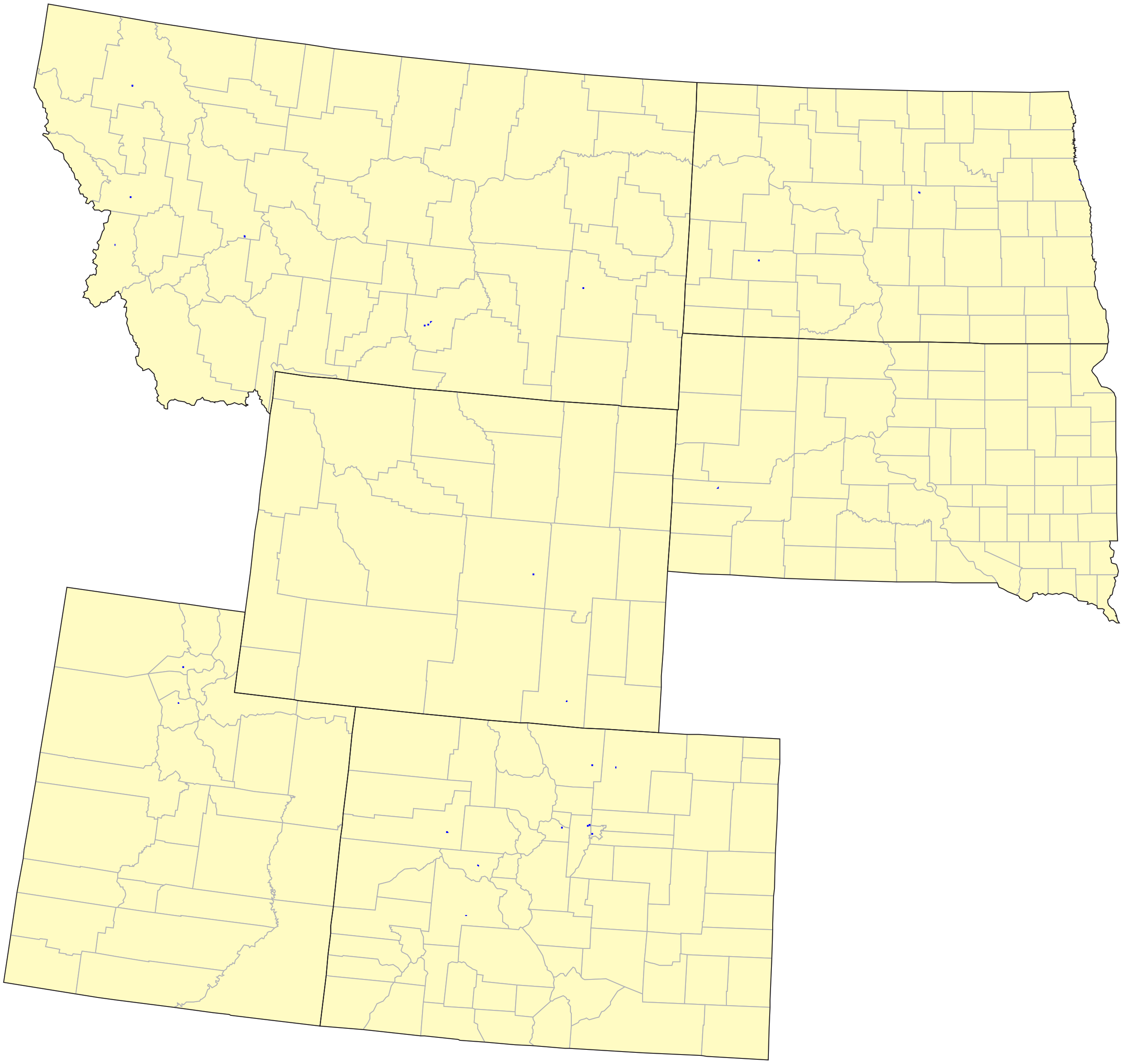
USEPA Region 8: Upper 30%

Vulnerability Index 1: Density of Service Stations
(stations per square mile)



USEPA Region 8: Upper 10%

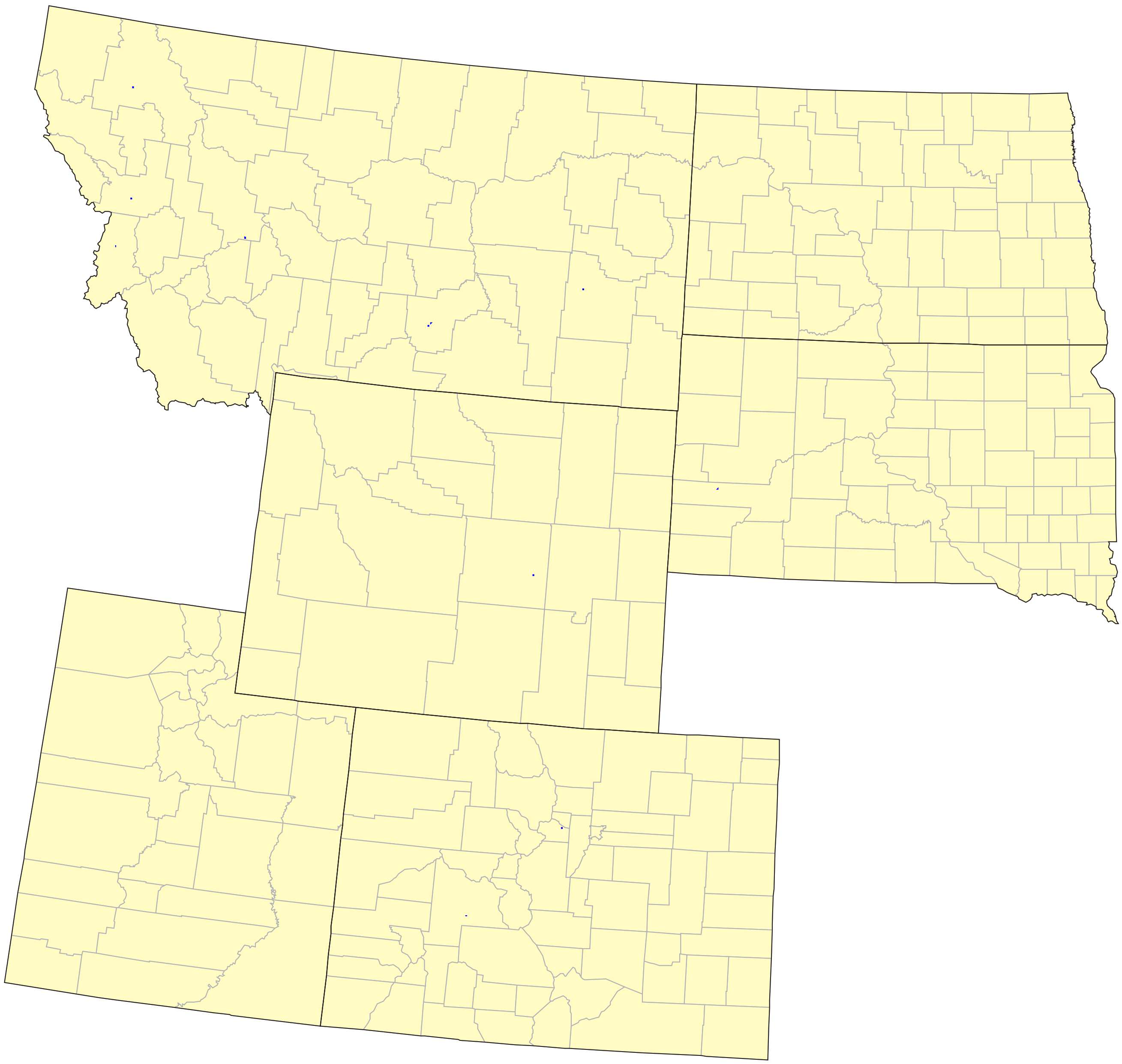
Vulnerability Index 1: Density of Service Stations
(stations per square mile)



USEPA Region 8: Upper 3%

Vulnerability Index 1: Density of Service Stations

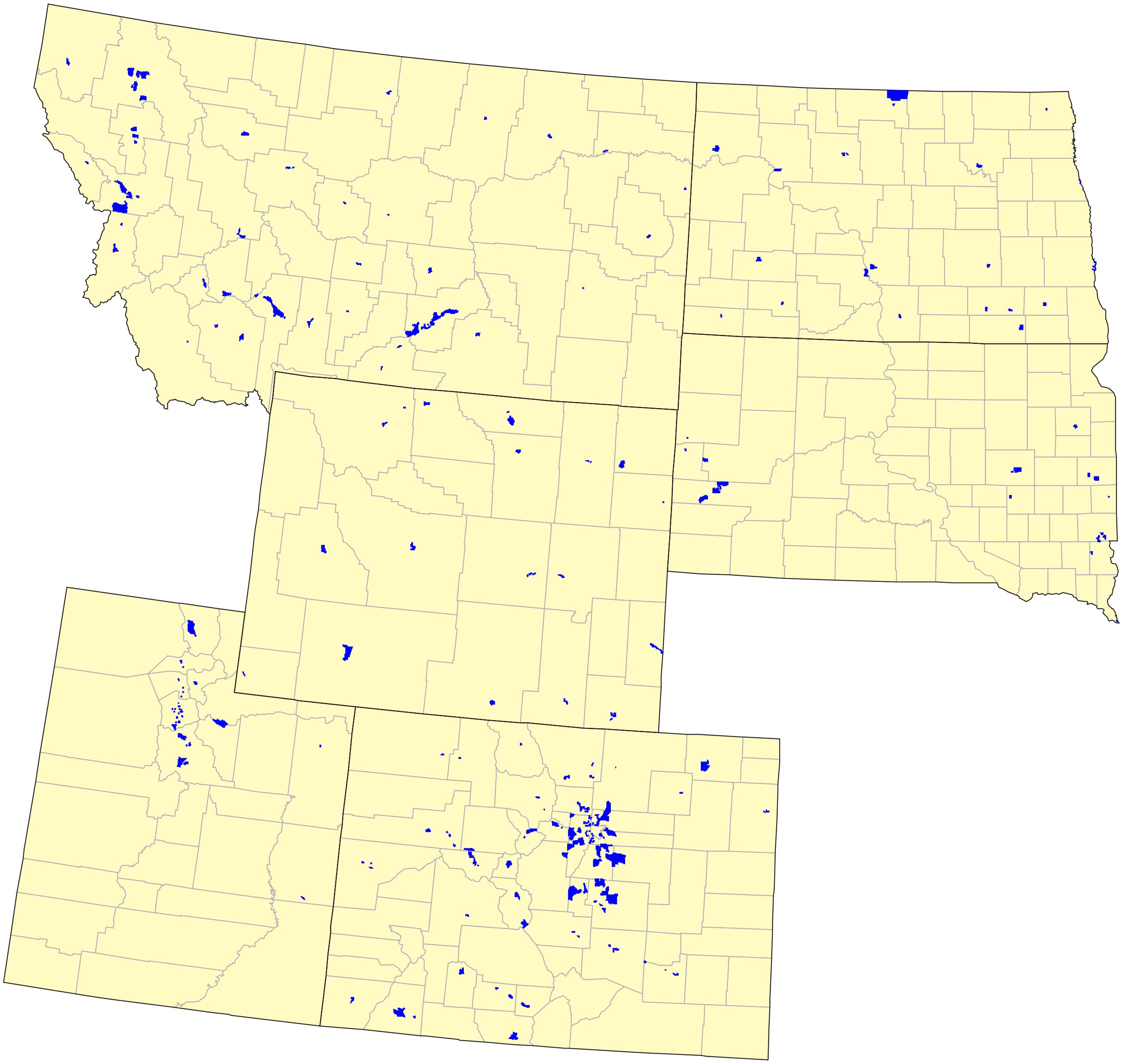
(stations per square mile)



USEPA Region 8: Upper 1%

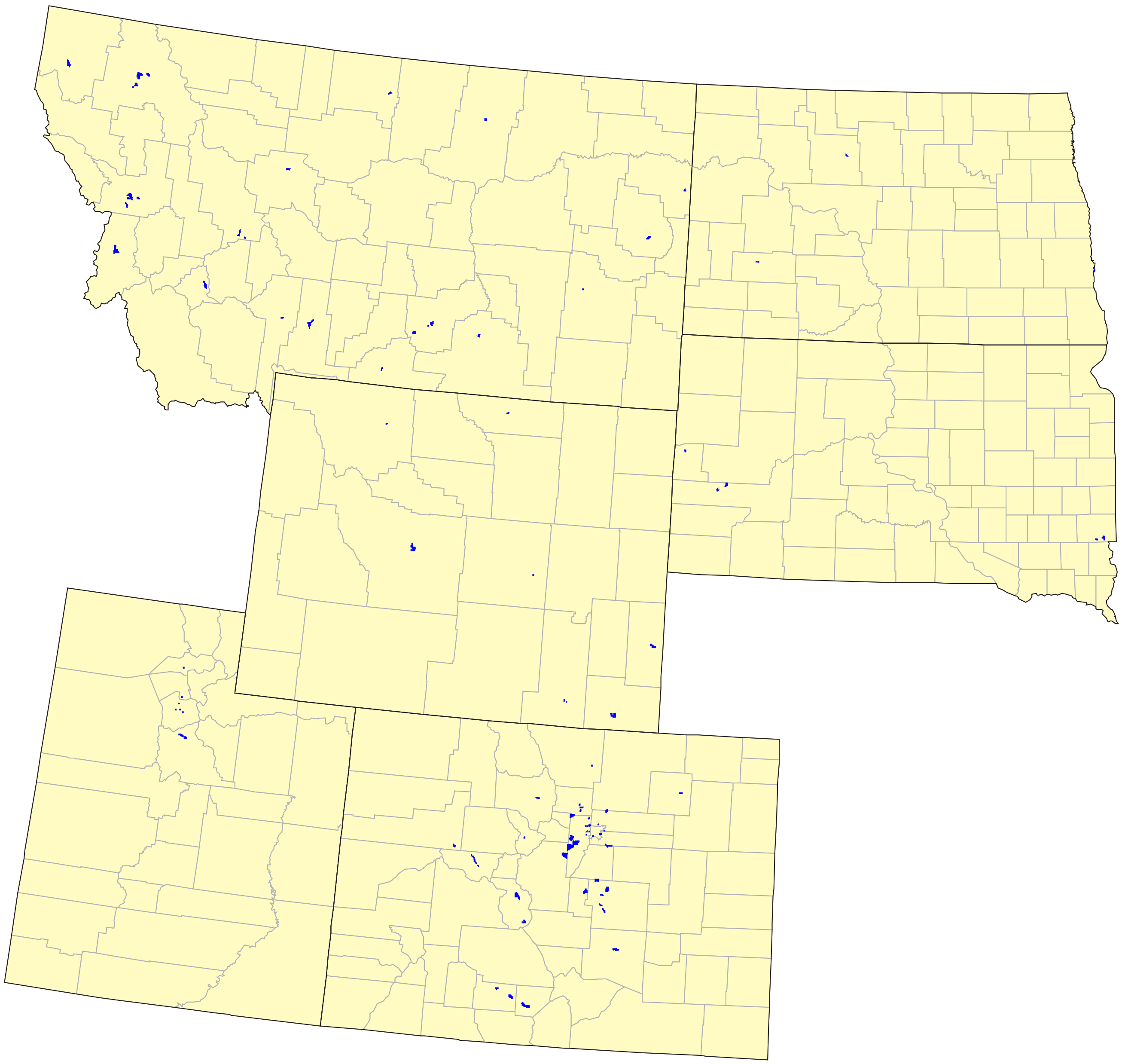
Vulnerability Index 1: Density of Service Stations

(stations per square mile)



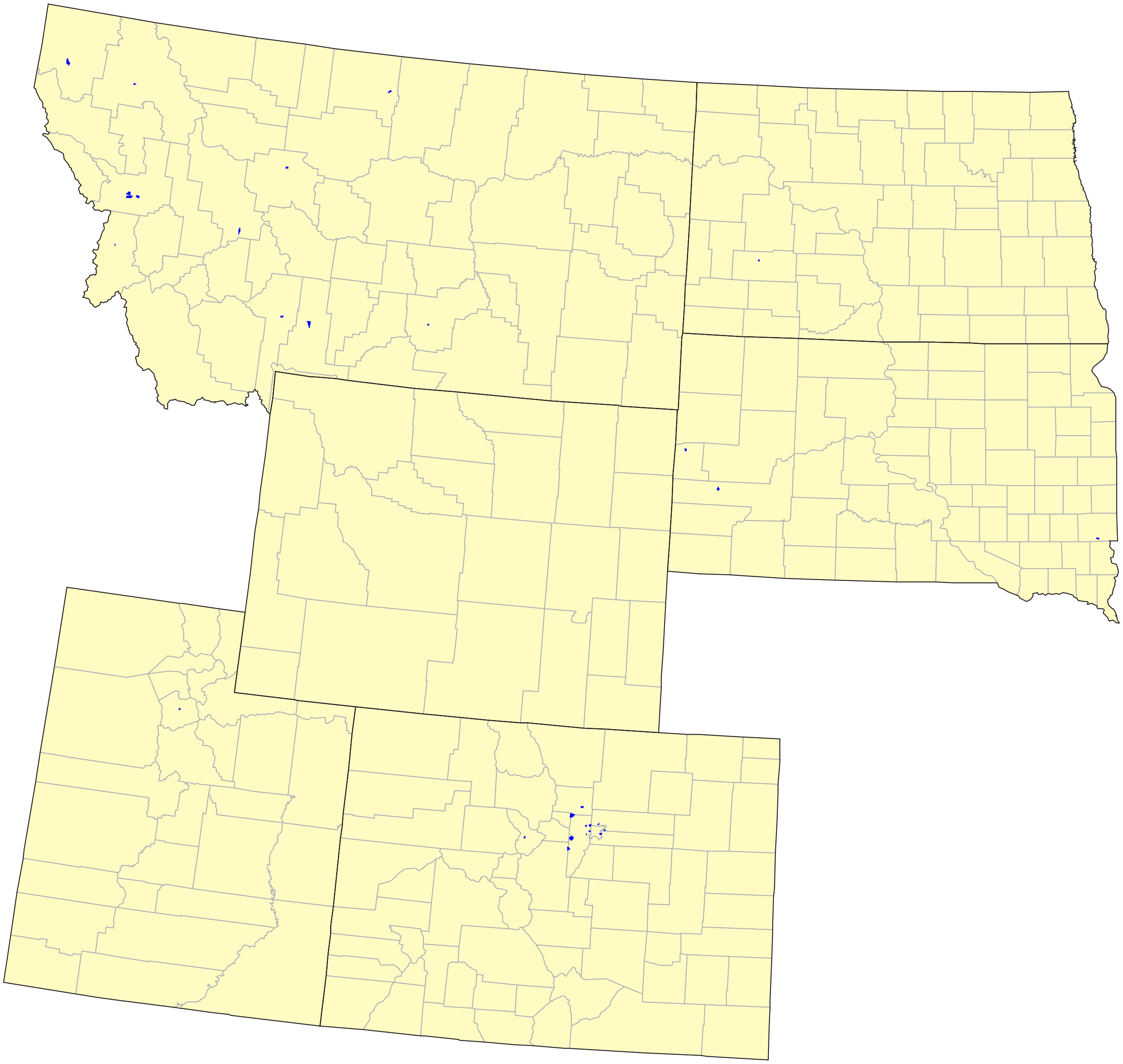
USEPA Region 8: Upper 30%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



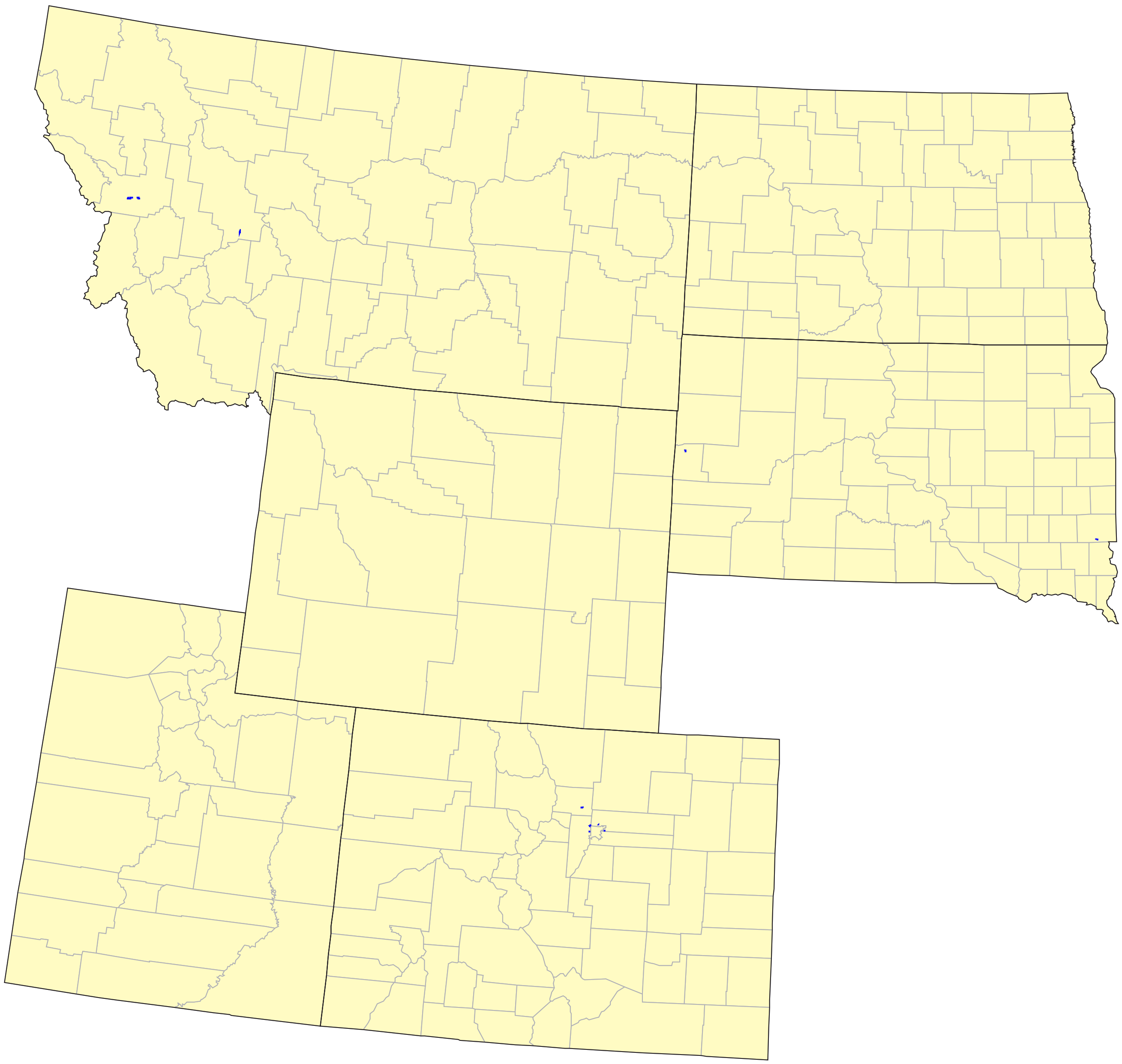
USEPA Region 8: Upper 10%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



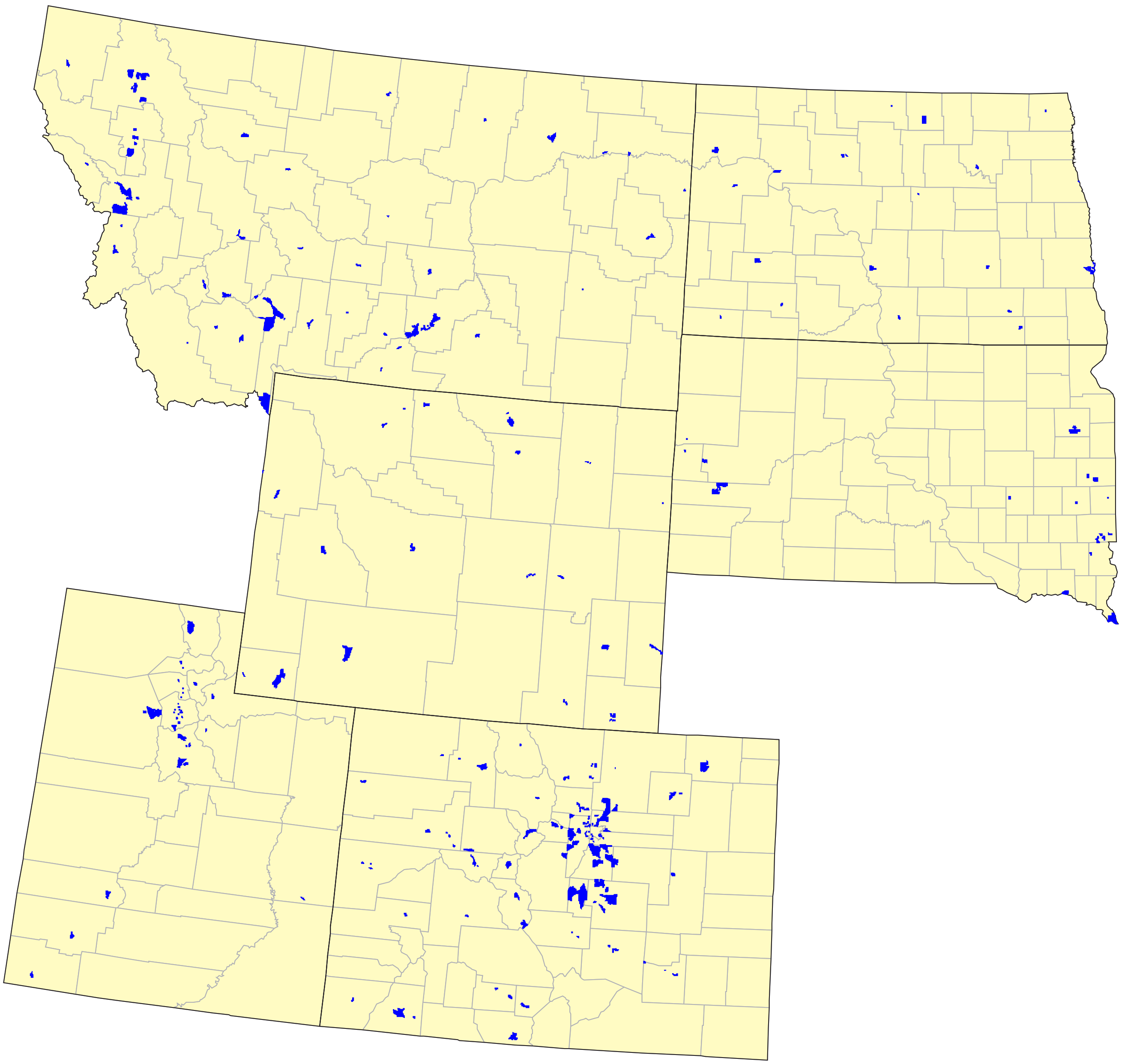
USEPA Region 8: Upper 3%

Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)

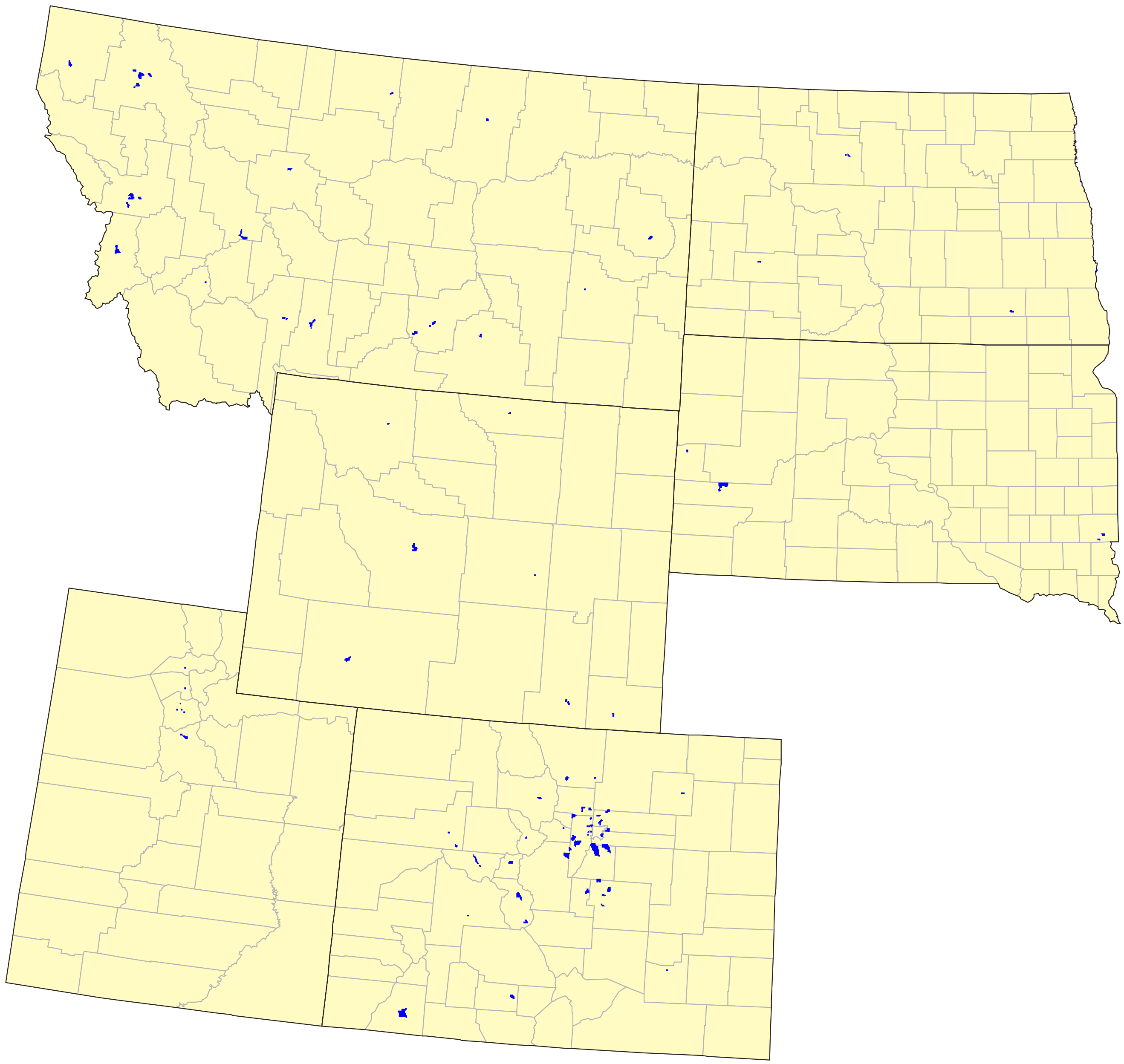


USEPA Region 8: Upper 1%

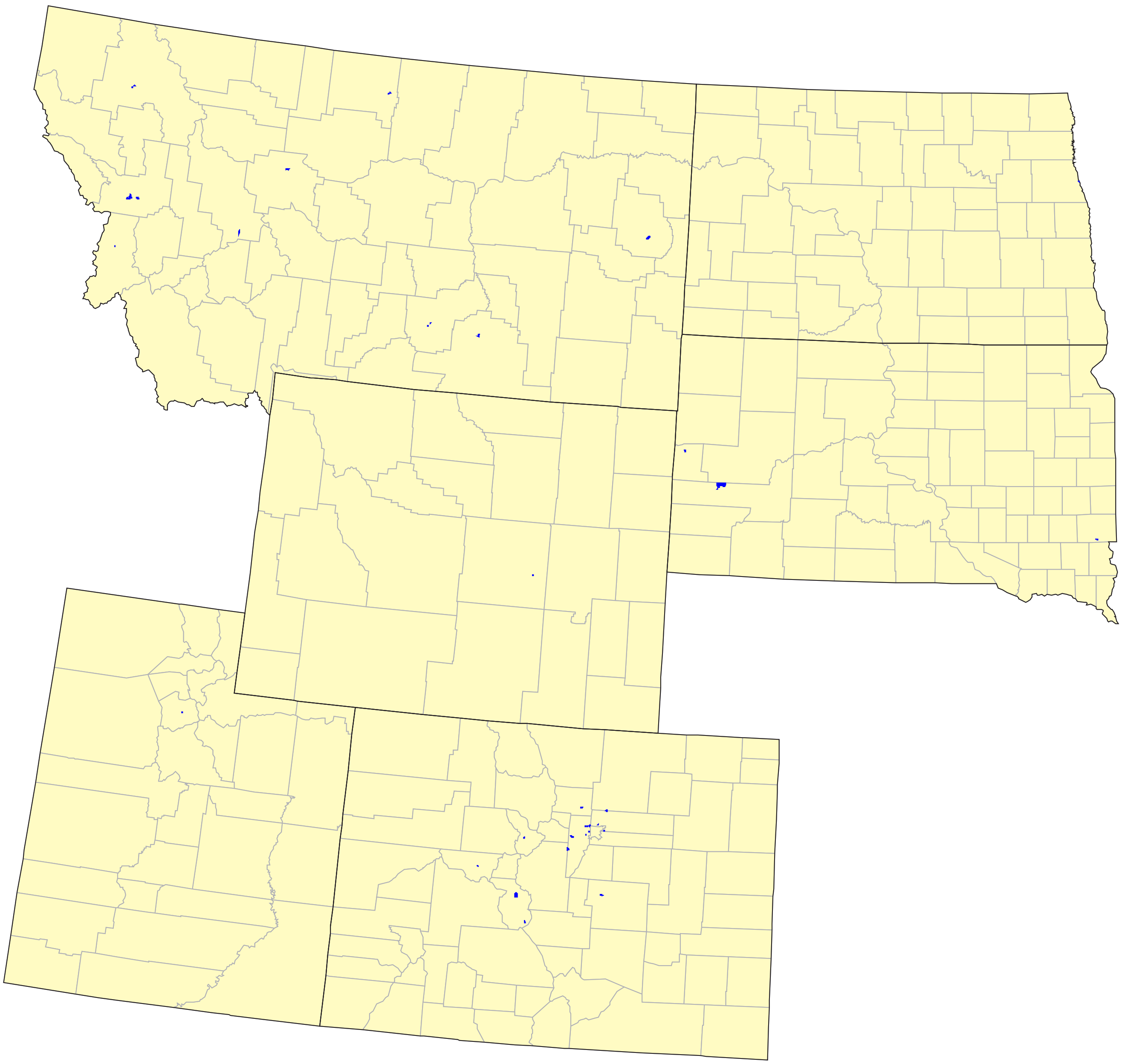
Vulnerability Index 2: Density of Households using Water from a Private Source (households per square mile)



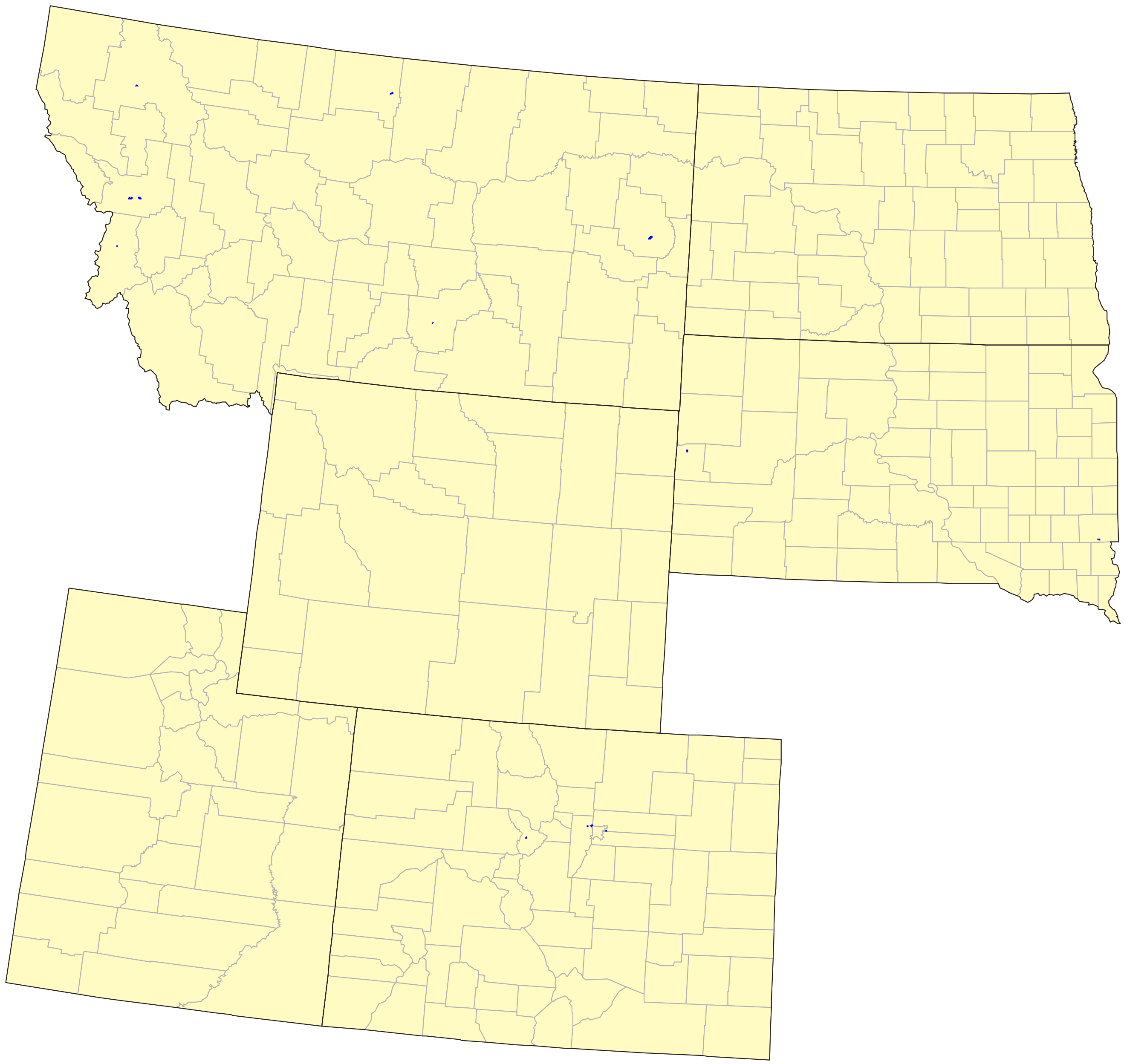
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 8: Upper 30%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 8: Upper 10%



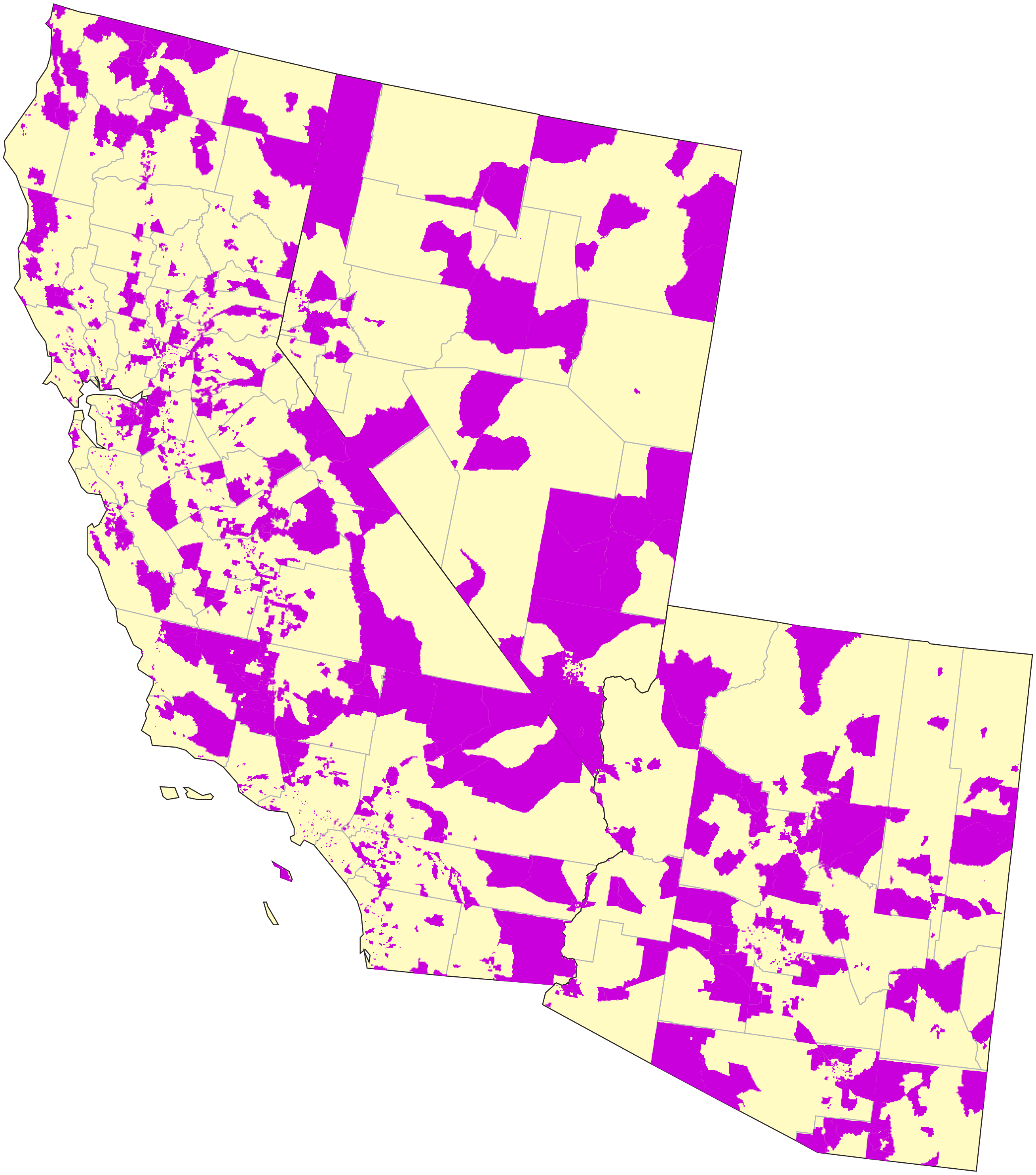
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 8: Upper 3%



Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$ USEPA Region 8: Upper 1%

Appendix J

USEPA Region 9 Vulnerability



1990 US Census Blocks that contain BOTH Consumers of Shallow Drinking Water and Service Stations

USEPA Region 9: Upper 30%

Vulnerability Index 1: Density of Service Stations

USEPA Region 9: Upper 10%

Vulnerability Index 1: Density of Service Stations

USEPA Region 9: Upper 3%

Vulnerability Index 1: Density of Service Stations


USEPA Region 9: Upper 1%

Vulnerability Index 1: Density of Service Stations

USEPA Region 9: Upper 30%

Vulnerability Index 2: Density of Consumers of Shallow Drinking Water

USEPA Region 9: Upper 10%

Vulnerability Index 2: Density of Consumers of Shallow Drinking Water

USEPA Region 9: Upper 3%

Vulnerability Index 2: Density of Consumers of Shallow Drinking Water

USEPA Region 9: Upper 1%

Vulnerability Index 2: Density of Consumers of Shallow Drinking Water

Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Consumers}}{\text{Surface Area}}$ USEPA Region 9: Upper 30%

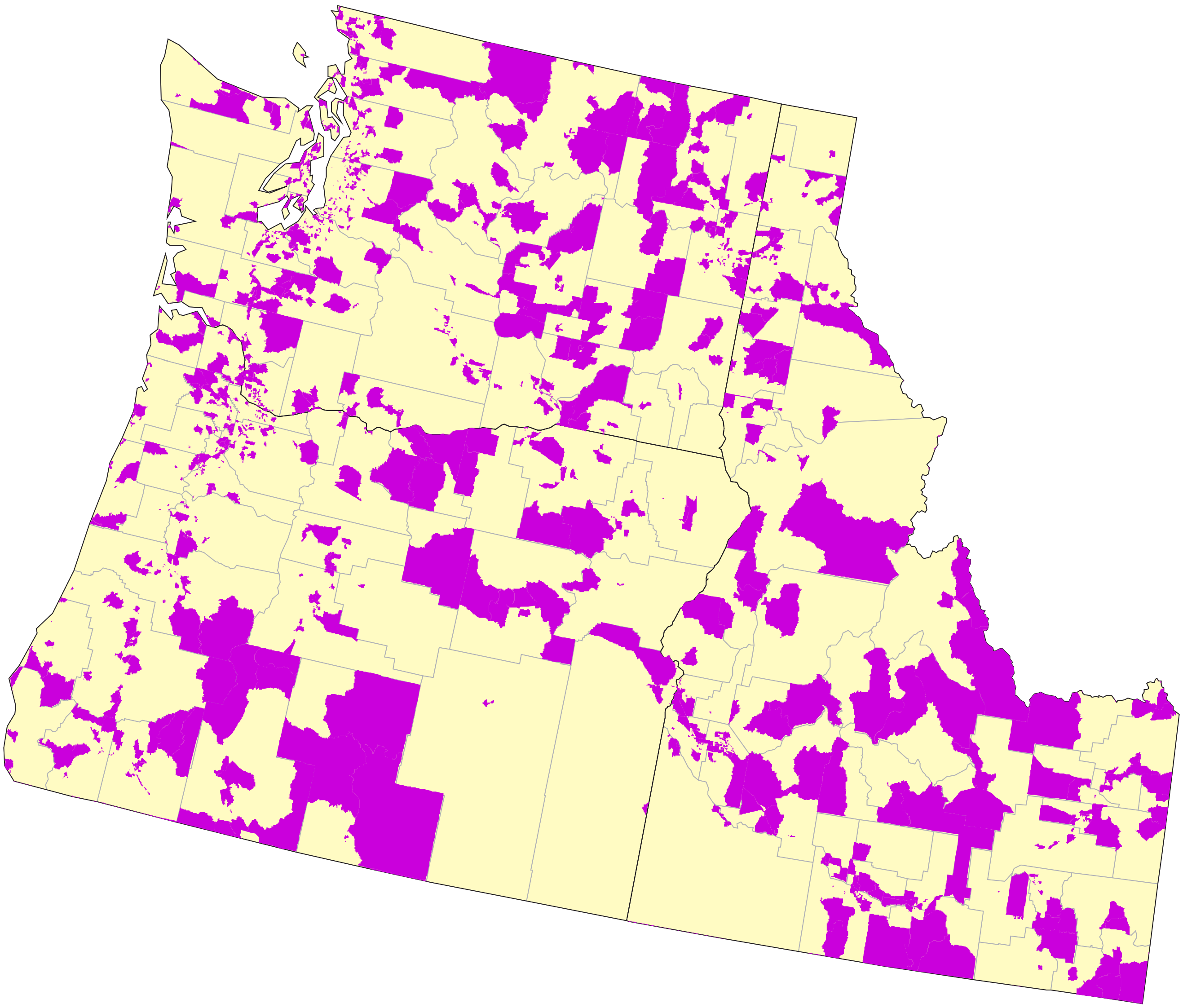
Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Consumers}}{\text{Surface Area}}$ USEPA Region 9: Upper 10%

Vulnerability Index 3: $\frac{\text{\# Service Stations * \# Consumers}}{\text{Surface Area}}$ USEPA Region 9: Upper 3%

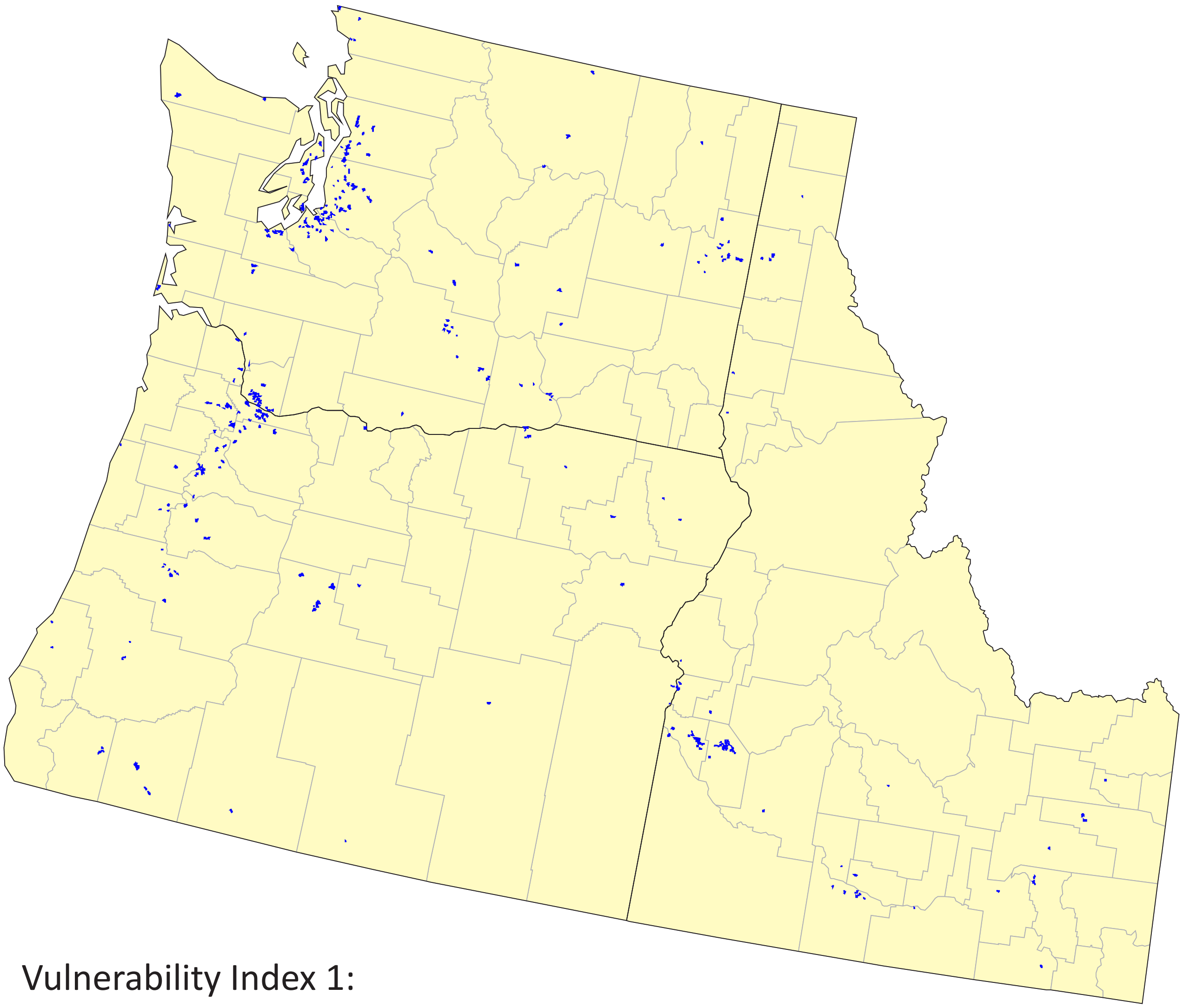
Vulnerability Index 3: $\frac{\underline{\text{\# Service Stations * \# Consumers}}}{\text{Surface Area}}$ USEPA Region 9: Upper 1%

Appendix K

USEPA Region 10 Vulnerability



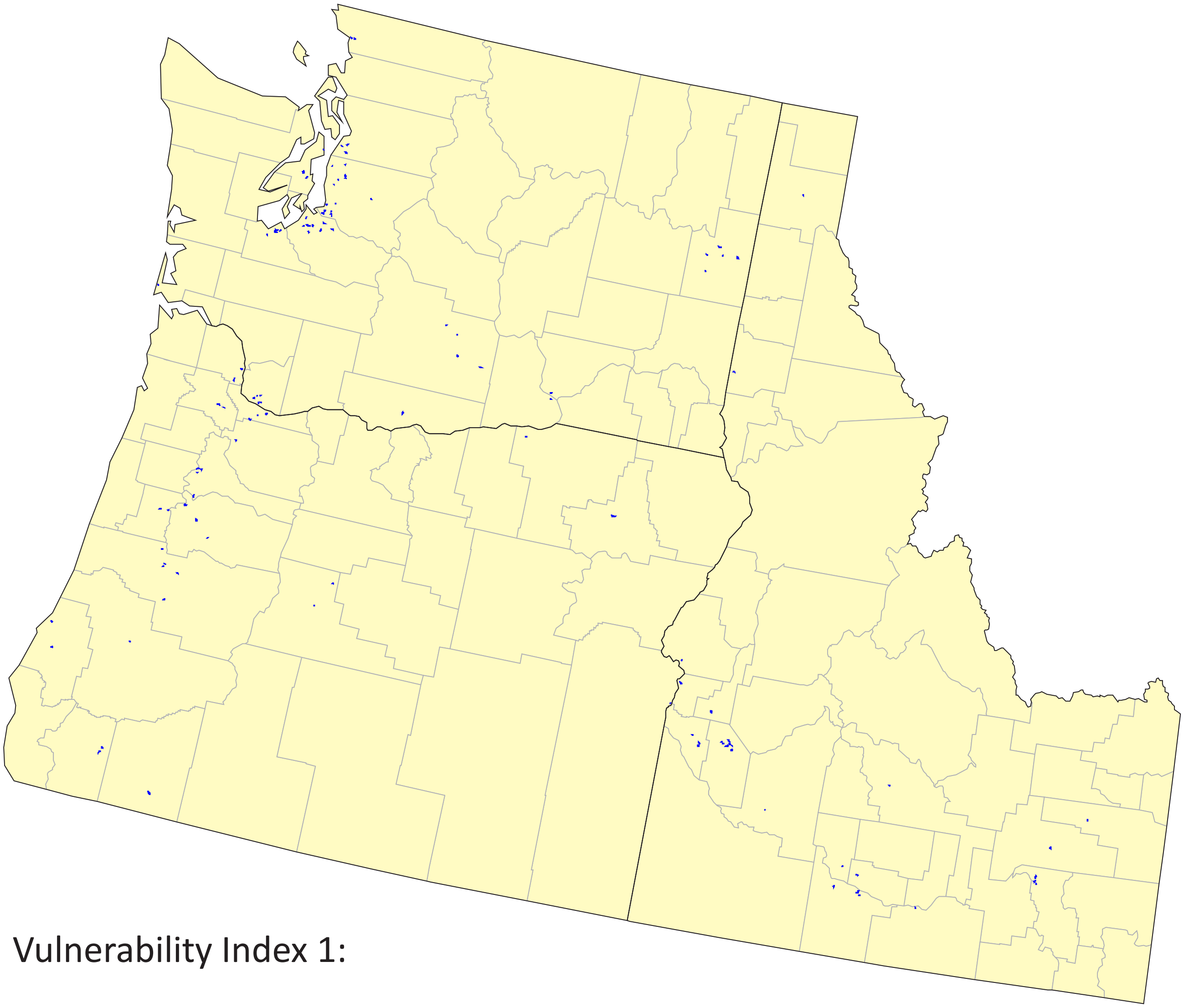
1990 US Census Blocks that contain BOTH Consumers
of Shallow Drinking Water and Service Stations



Vulnerability Index 1:

Density of Service Stations
(stations per square mile)

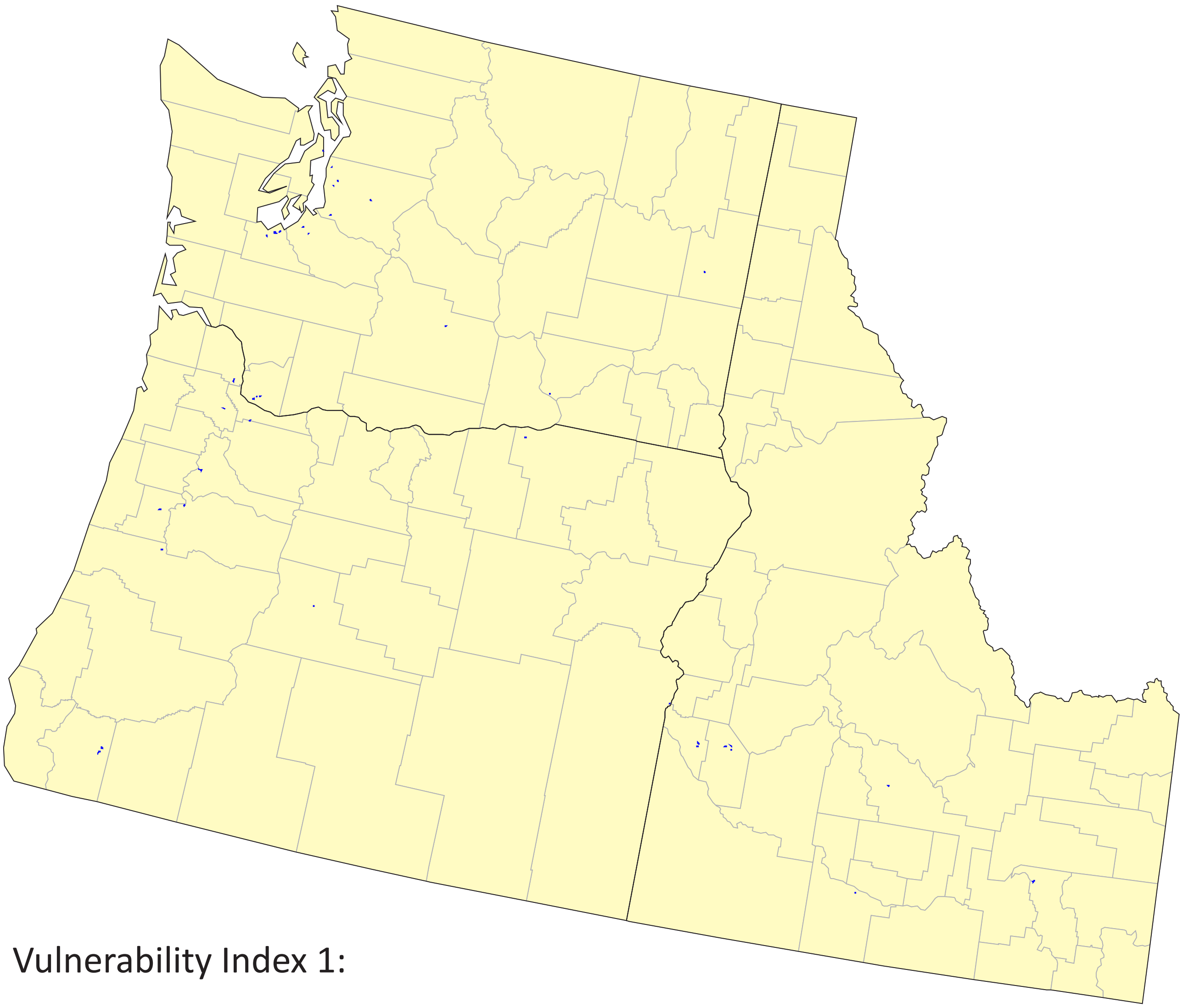
USEPA Region 10 : Upper 30%



Vulnerability Index 1:

Density of Service Stations
(stations per square mile)

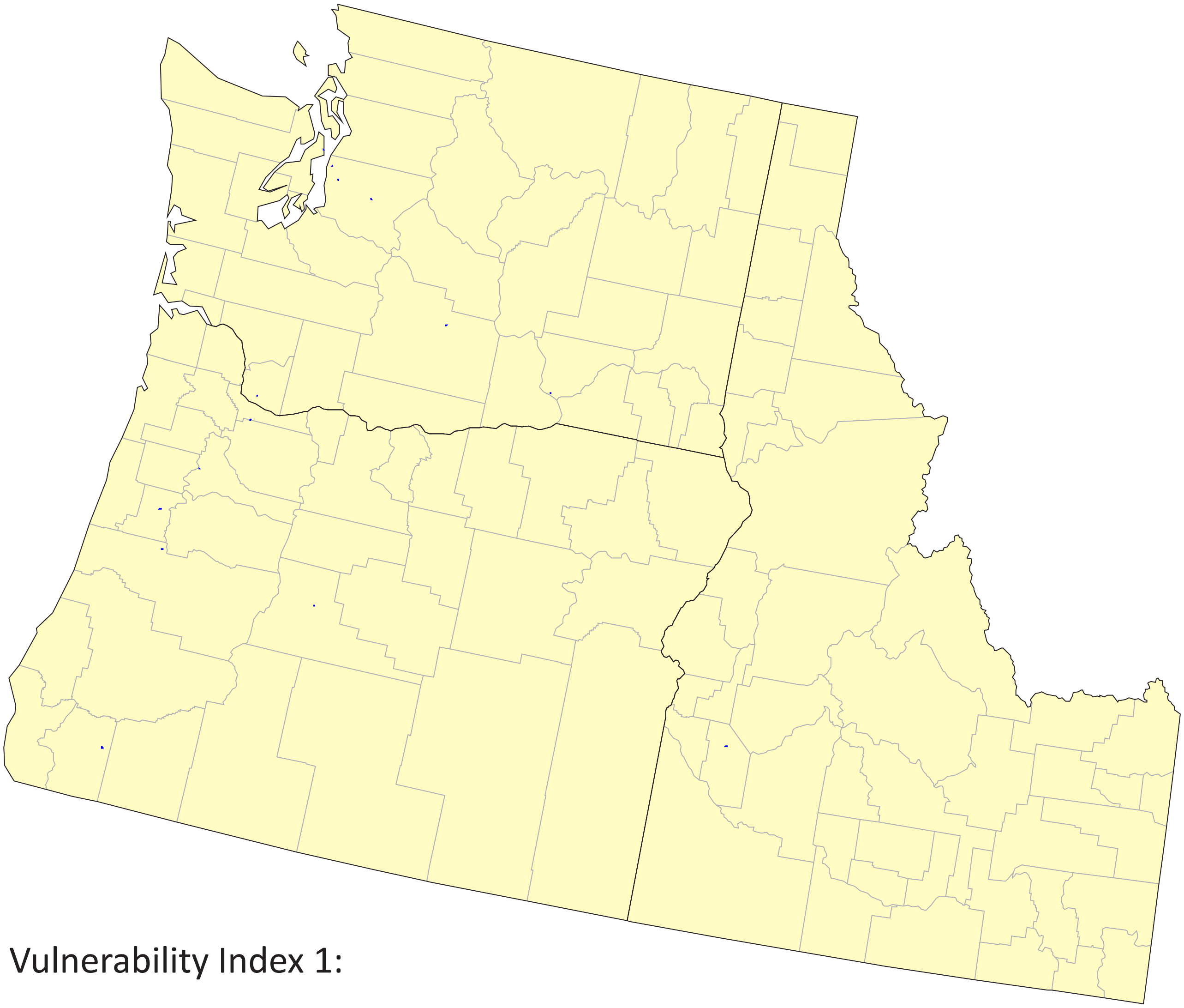
USEPA Region 10 : Upper 10%



Vulnerability Index 1:

Density of Service Stations
(stations per square mile)

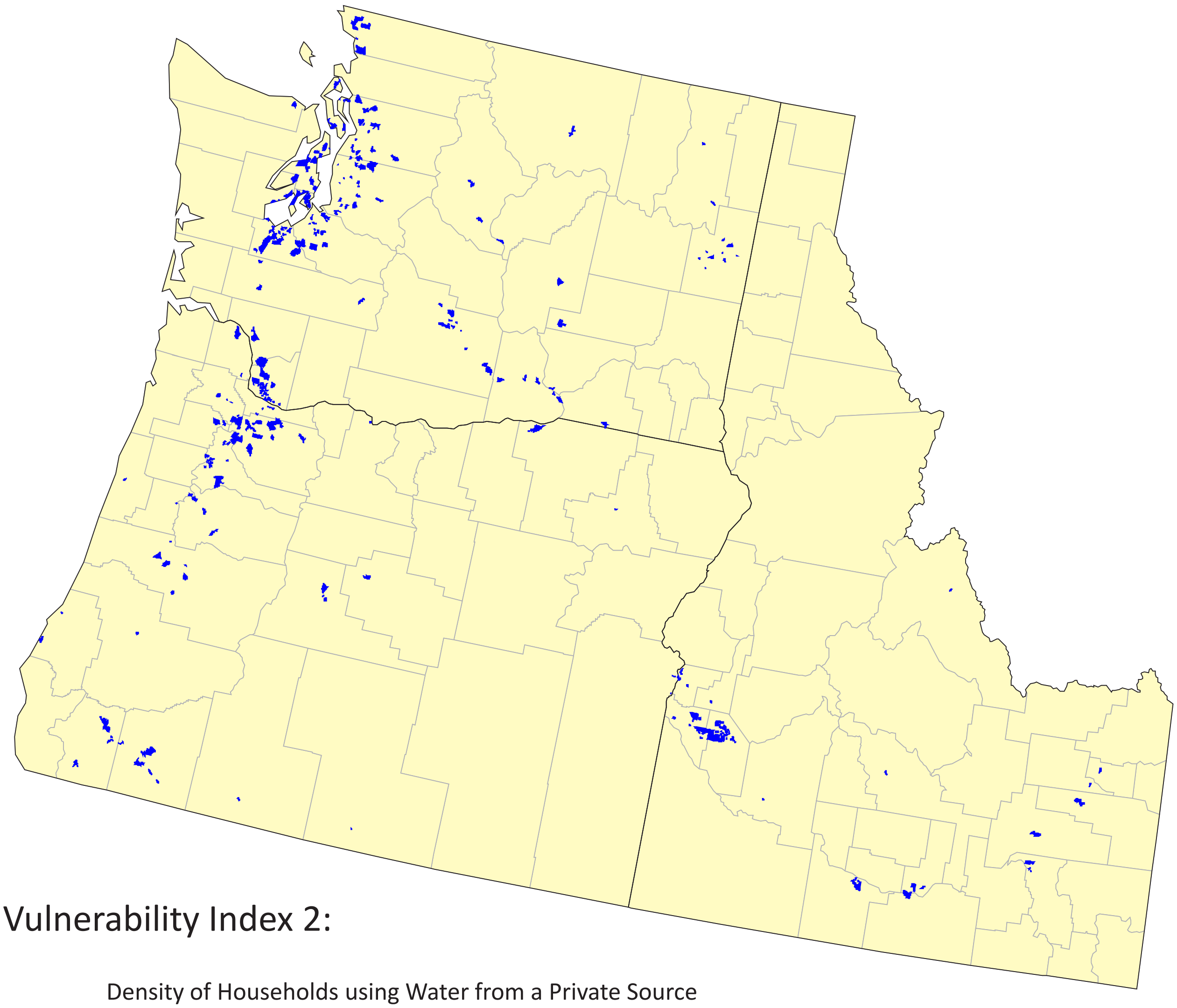
USEPA Region 10 : Upper 3%



Vulnerability Index 1:

Density of Service Stations
(stations per square mile)

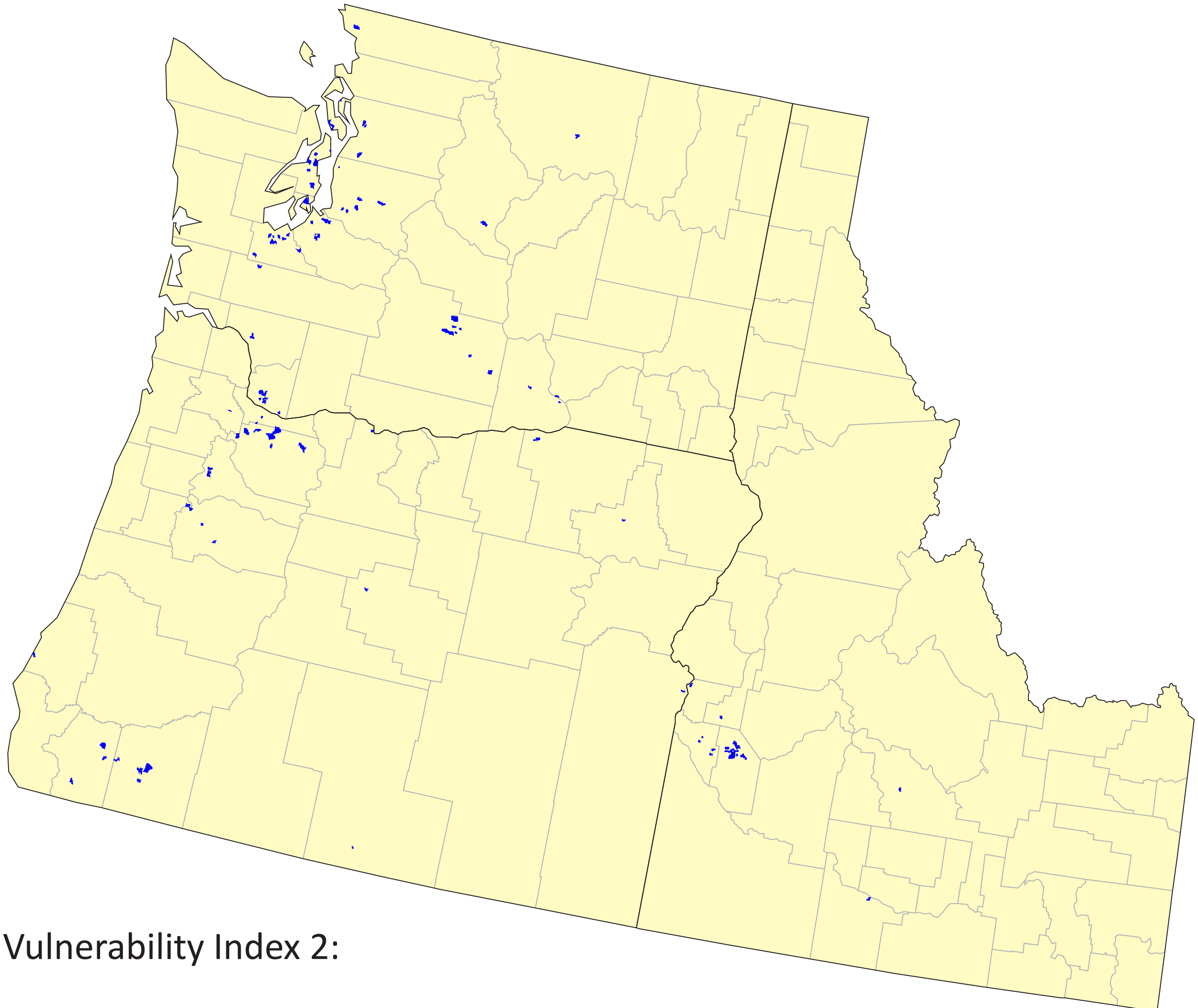
USEPA Region 10 : Upper 1%



Vulnerability Index 2:

Density of Households using Water from a Private Source
(households per square mile)

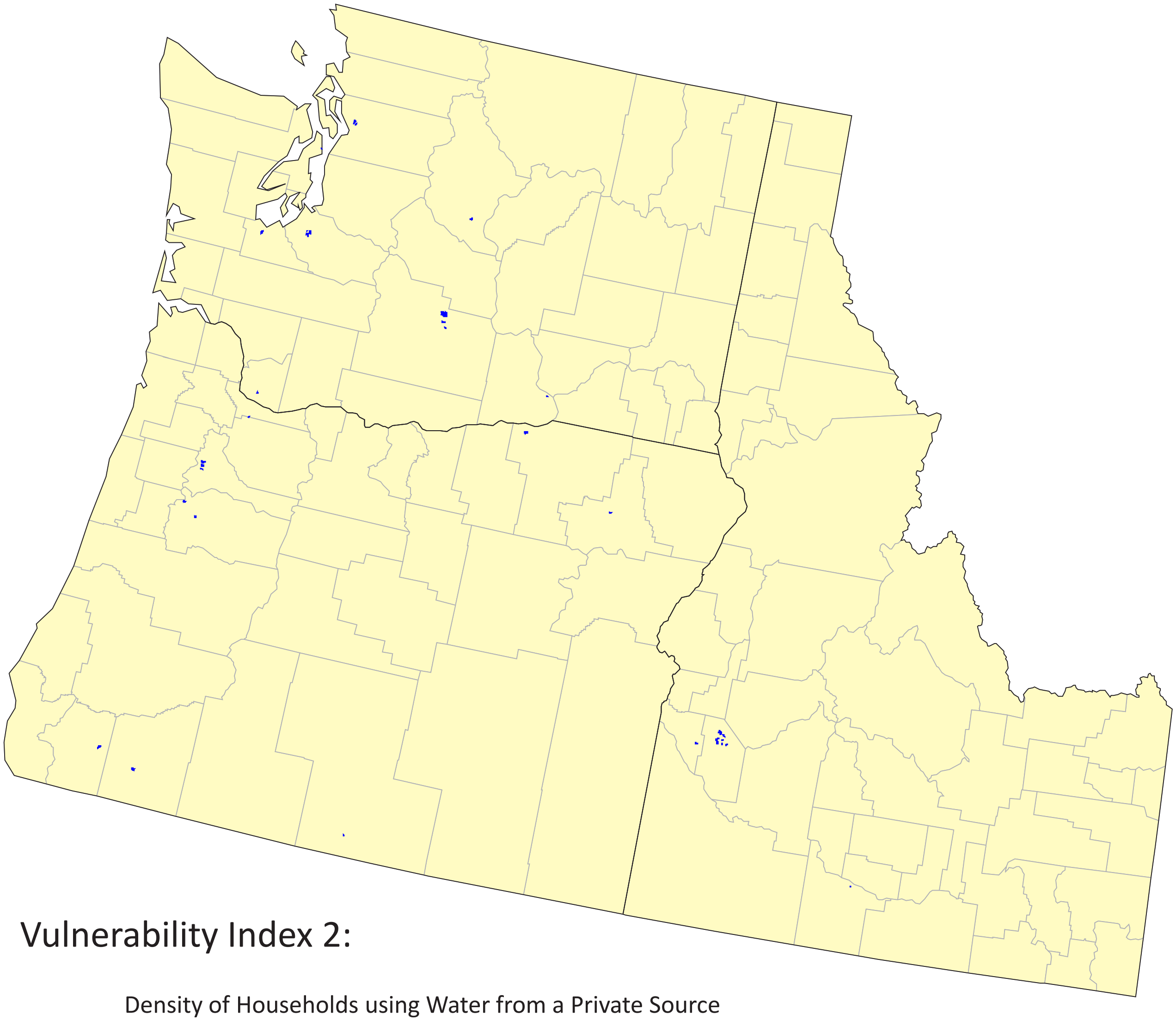
USEPA Region 10 : Upper 30%



Vulnerability Index 2:

Density of Households using Water from a Private Source
(households per square mile)

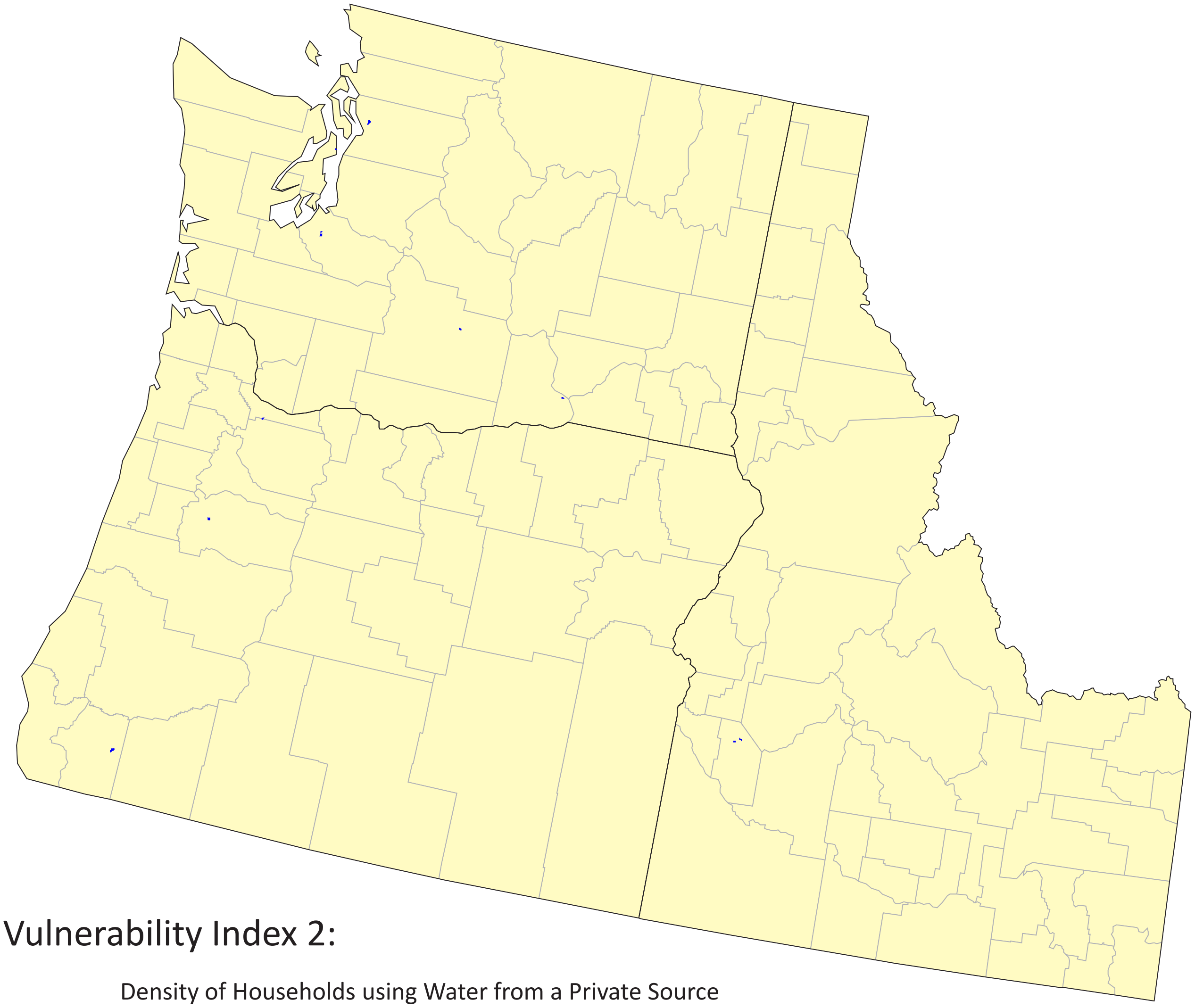
USEPA Region 10 : Upper 10%



Vulnerability Index 2:

Density of Households using Water from a Private Source
(households per square mile)

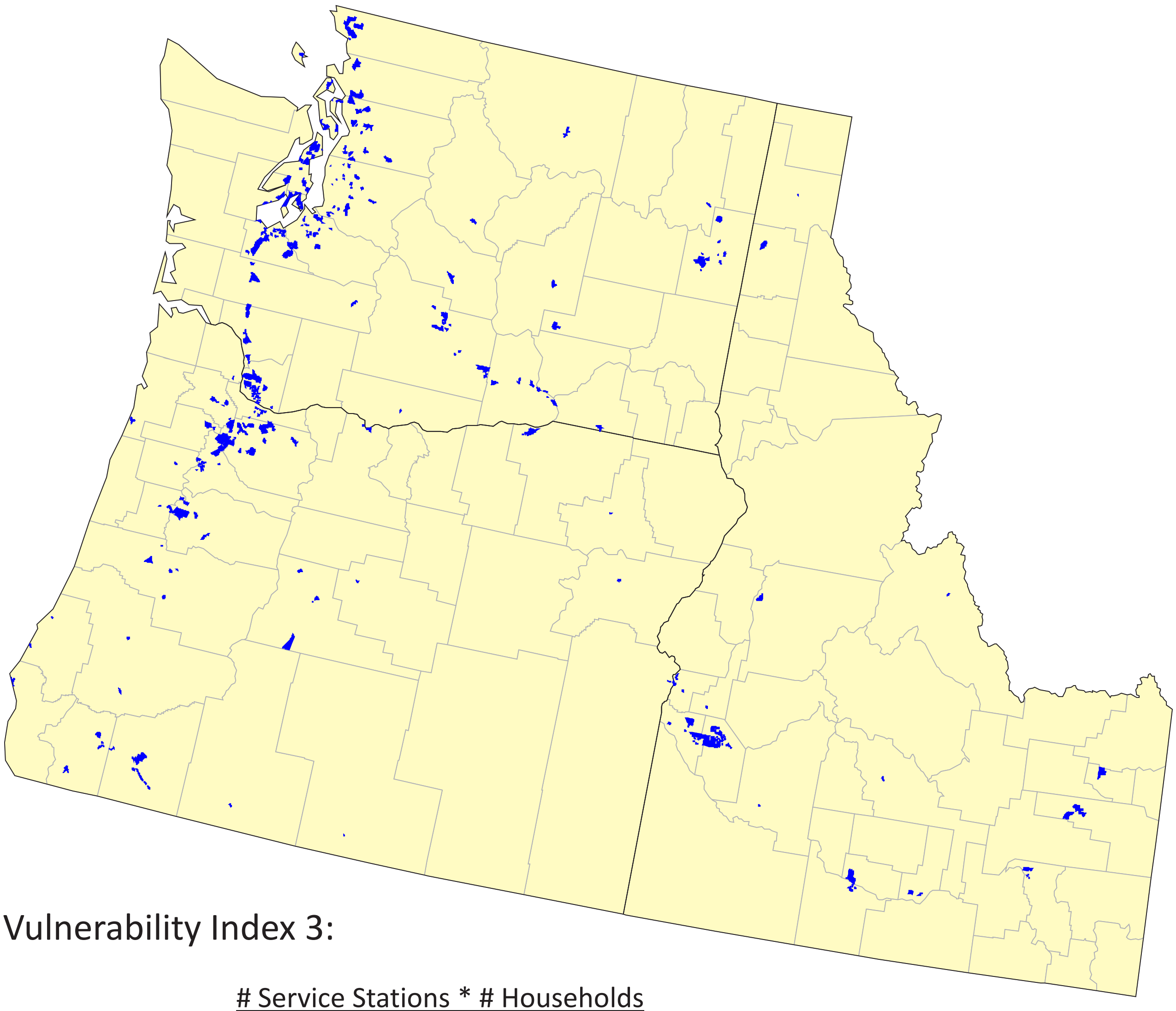
USEPA Region 10 : Upper 3%



Vulnerability Index 2:

Density of Households using Water from a Private Source
(households per square mile)

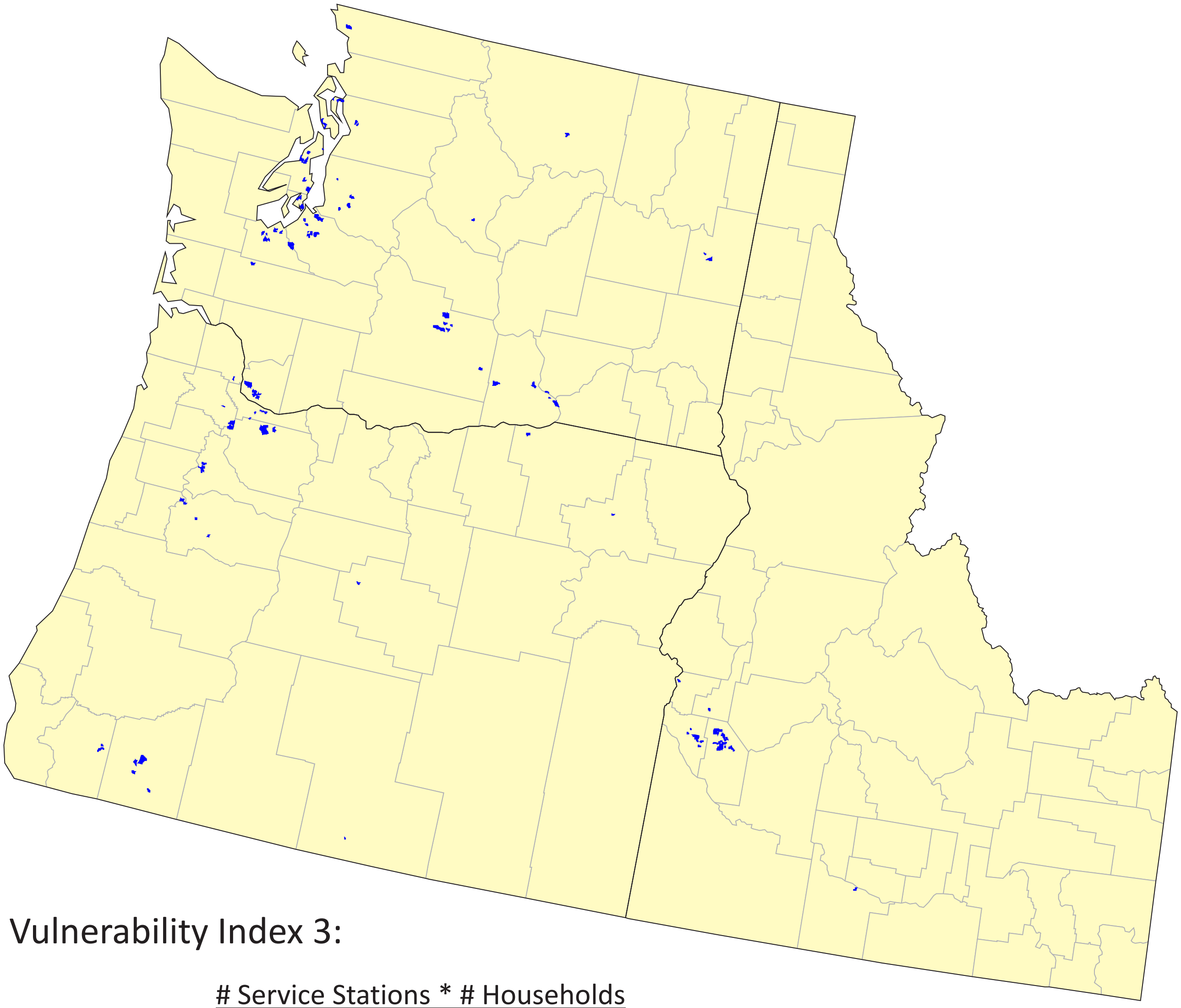
USEPA Region 10 : Upper 1%



Vulnerability Index 3:

$$\frac{\#\ \text{Service Stations} * \#\ \text{Households}}{\text{Surface Area}}$$

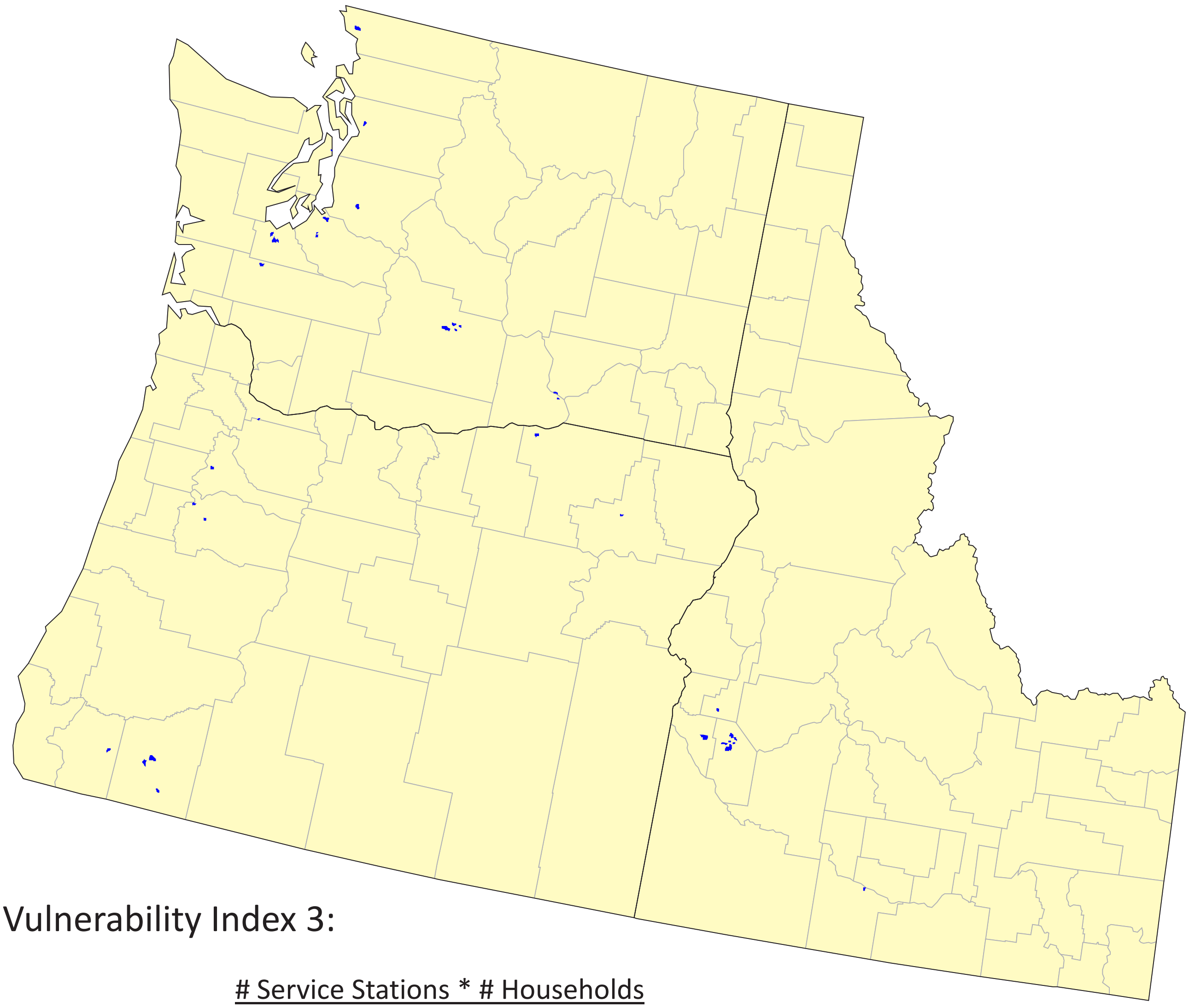
USEPA Region 10 : Worst 30%



Vulnerability Index 3:

$$\frac{\text{\# Service Stations * \# Households}}{\text{Surface Area}}$$

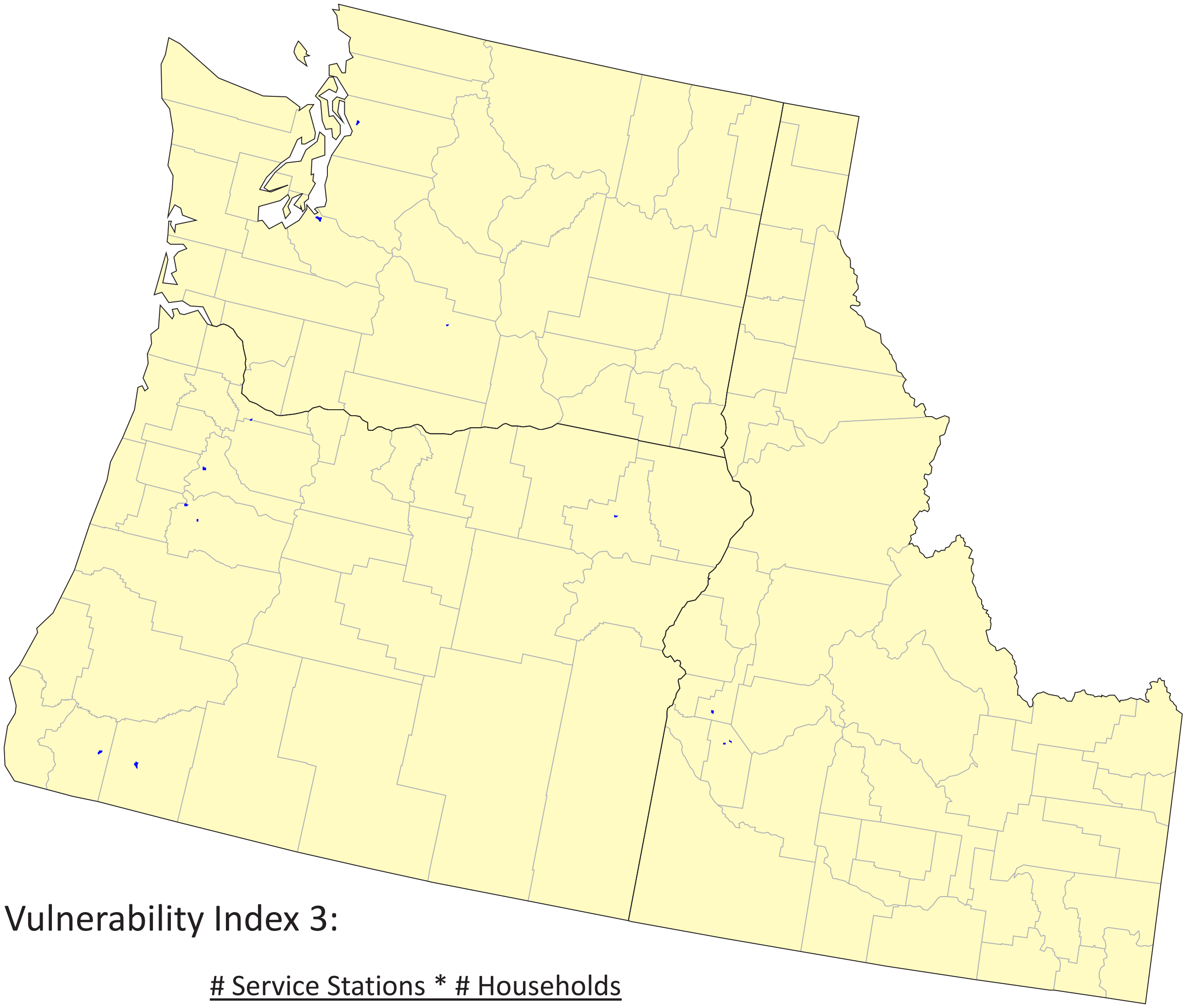
USEPA Region 10 : Worst 10%



Vulnerability Index 3:

$$\frac{\text{\# Service Stations} * \text{\# Households}}{\text{Surface Area}}$$

USEPA Region 10 : Worst 3%



Vulnerability Index 3:

$$\frac{\#\text{ Service Stations} * \#\text{ Households}}{\text{Surface Area}}$$

USEPA Region 10 : Worst 1%

SCIENCE

United States Environmental Protection Agency

PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT NO. G-35

Office of Research and Development (8101R)
Washington, DC 20460

Official Business
Penalty for Private Use
$300