



FLUCTUATIONS OF GROUNDWATER OF THE  
CONTIGUOUS UNITED STATES; REGIONS DEFINED BY  
THE E.P.A., U.S.G.S., AND U.S.D.A. MONITORED BY  
GRACE –FO 2019-2021

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# MEASURING GROUNDWATER FLUCTUATIONS IN THE CONTINENTAL UNITED STATES VIA REMOTE SENSING

- Why is Groundwater important
  - Declining water resources
- Percentage of Water by type
  - Oceans and seas – 97.5%
  - Fresh Water – 2.5%
    - Surface water
    - Glaciers
    - Groundwater
- Agricultural irrigation practices are the largest user of groundwater in the U.S.



# WATER CONFLICTS

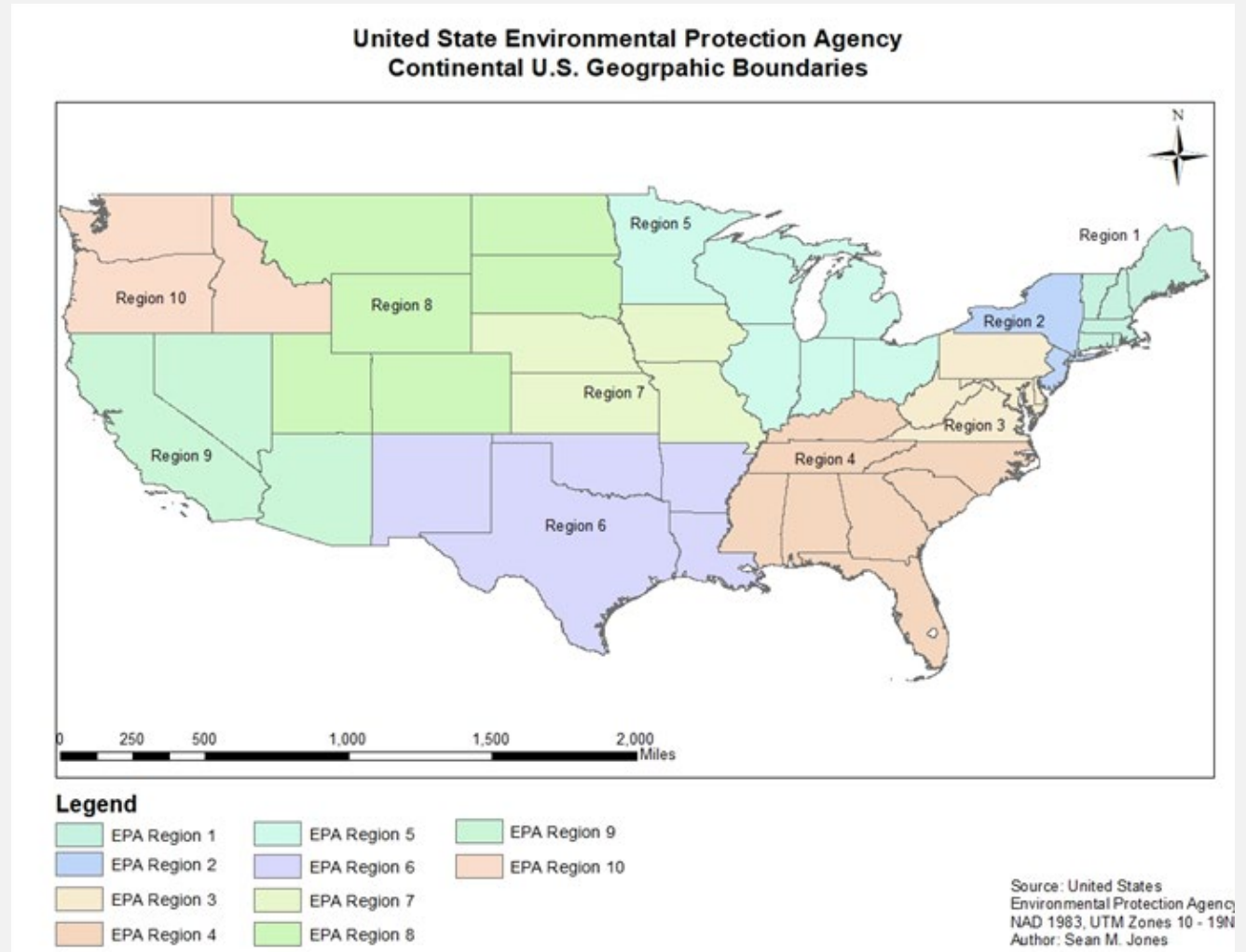
- Global
  - 4 billion people live in water scarce regions
- Nationally
  - Georgia
  - Colorado River Compact
    - Upper basin
    - Lower Basin
  - Grain Belt
    - Ogallala Aquifer
  - 1,000,000 Americans don't have access to water
- Droughts are becoming the new normal
  - over 50% of America is in a drought.

# SCOPE

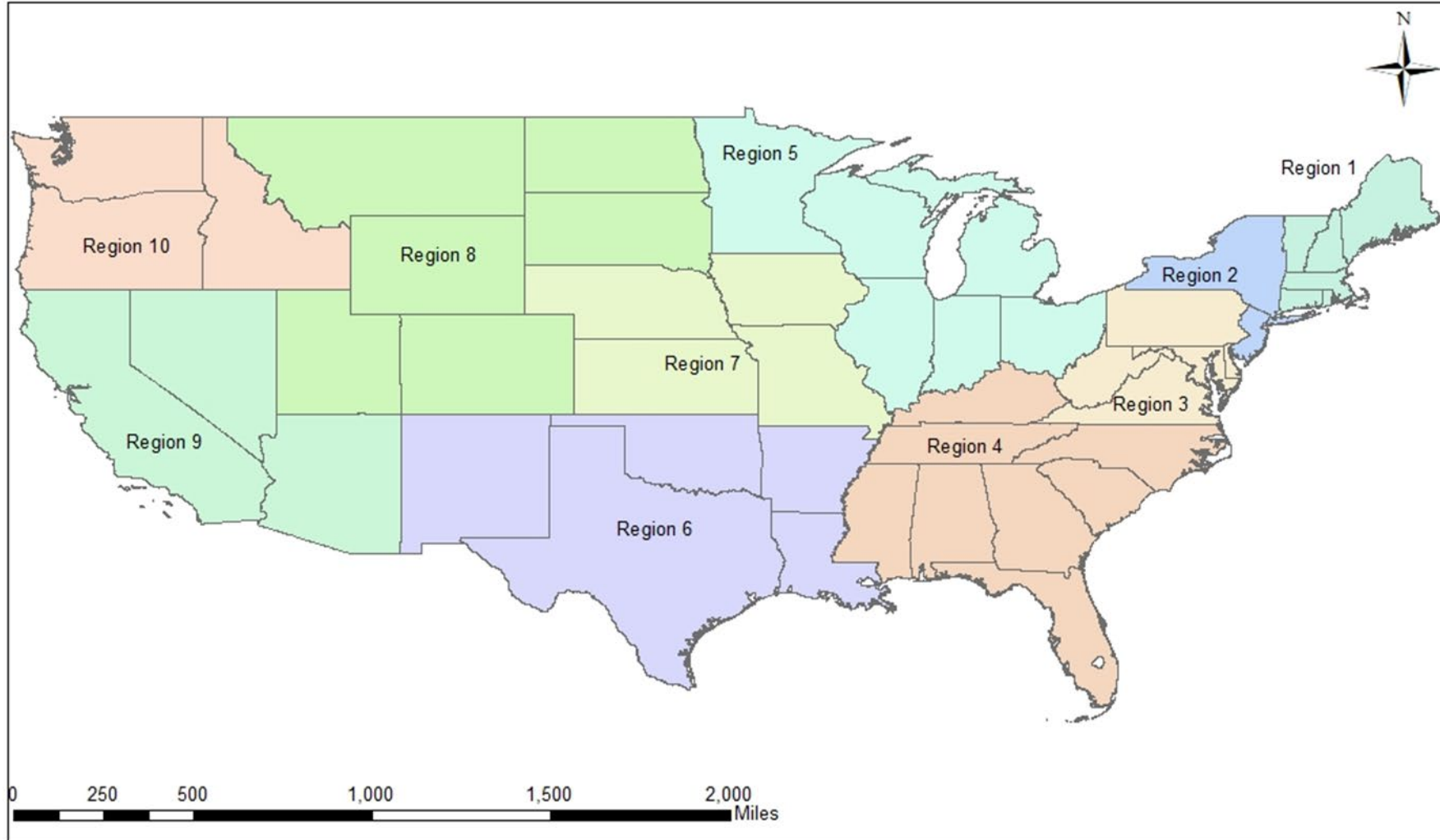
- Continental United States 2019-2021 groundwater fluctuations
- Comparison of three regulatory agencies divisions
  - EPA
    - Regulatory agency responsible for enforcing water quality Standards
  - USGS
    - Works to assess and monitor water resources and conditions
    - Incorporates a watershed/regional approach to their research, findings, and applications.
  - USDA
    - Responsible for Agriculture in America and USFS
- Deduce whether there is a statistically significant difference of Groundwater Height Equivalent means between Agency delineated regions.

# ENVIRONMENTAL PROTECTION AGENCY











- Responsible for:
  - Ambient Water Quality Standards
  - Enforcement of the Clean Water Act
  - Set standards for drinking water and ground water
  - Responsible for enforcing the Endangered Species Act.



# United State Environmental Protection Agency Continental U.S. Geogrphic Boundaries



## Legend

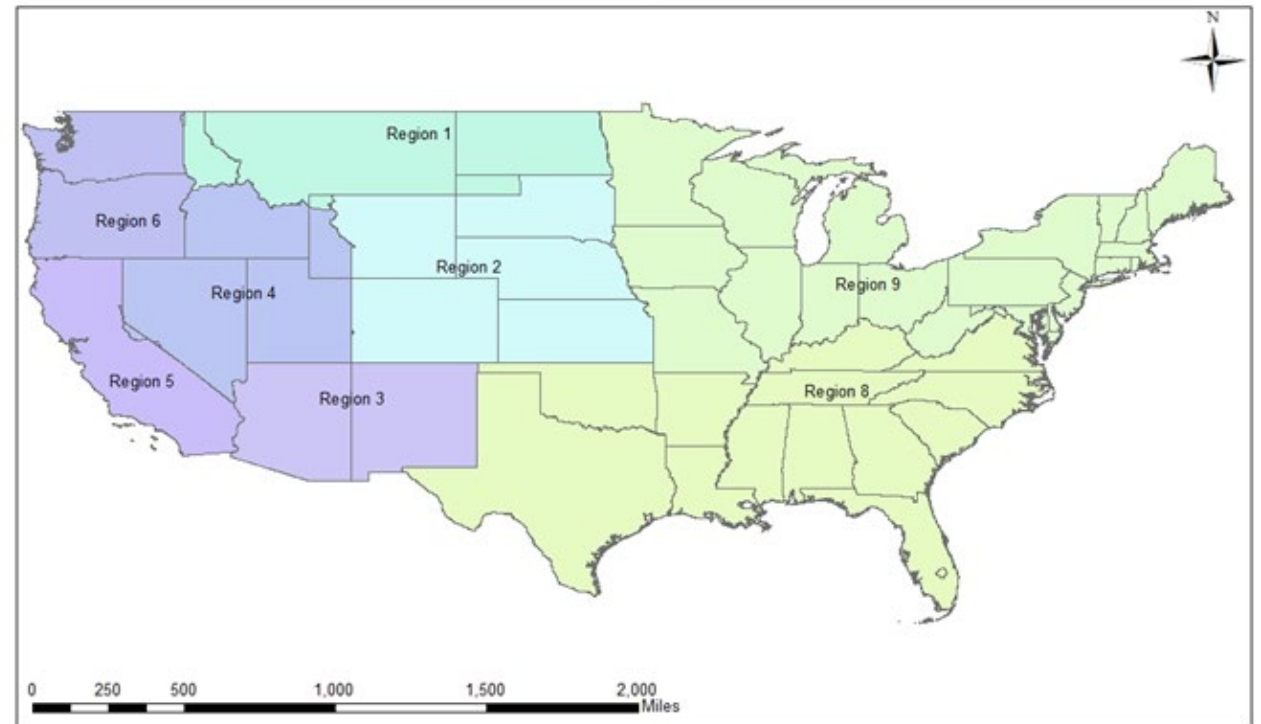
 EPA Region 1	 EPA Region 5	 EPA Region 9
 EPA Region 2	 EPA Region 6	 EPA Region 10
 EPA Region 3	 EPA Region 7	
 EPA Region 4	 EPA Region 8	

Source: United States  
Environmental Protection Agency  
NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones

# UNITED STATES DEPARTMENT OF AGRICULTURE

- Regulatory body for Agriculture
  - 2.3 Billion Acres are classified as agricultural.
- Decides and defines use for United States Forest Service.
  - 193 million acres
- Provides incentives for agriculture producers and non-industrial timber producers.

United States Department of Agriculture  
Continental U.S. Geographic Boundaries



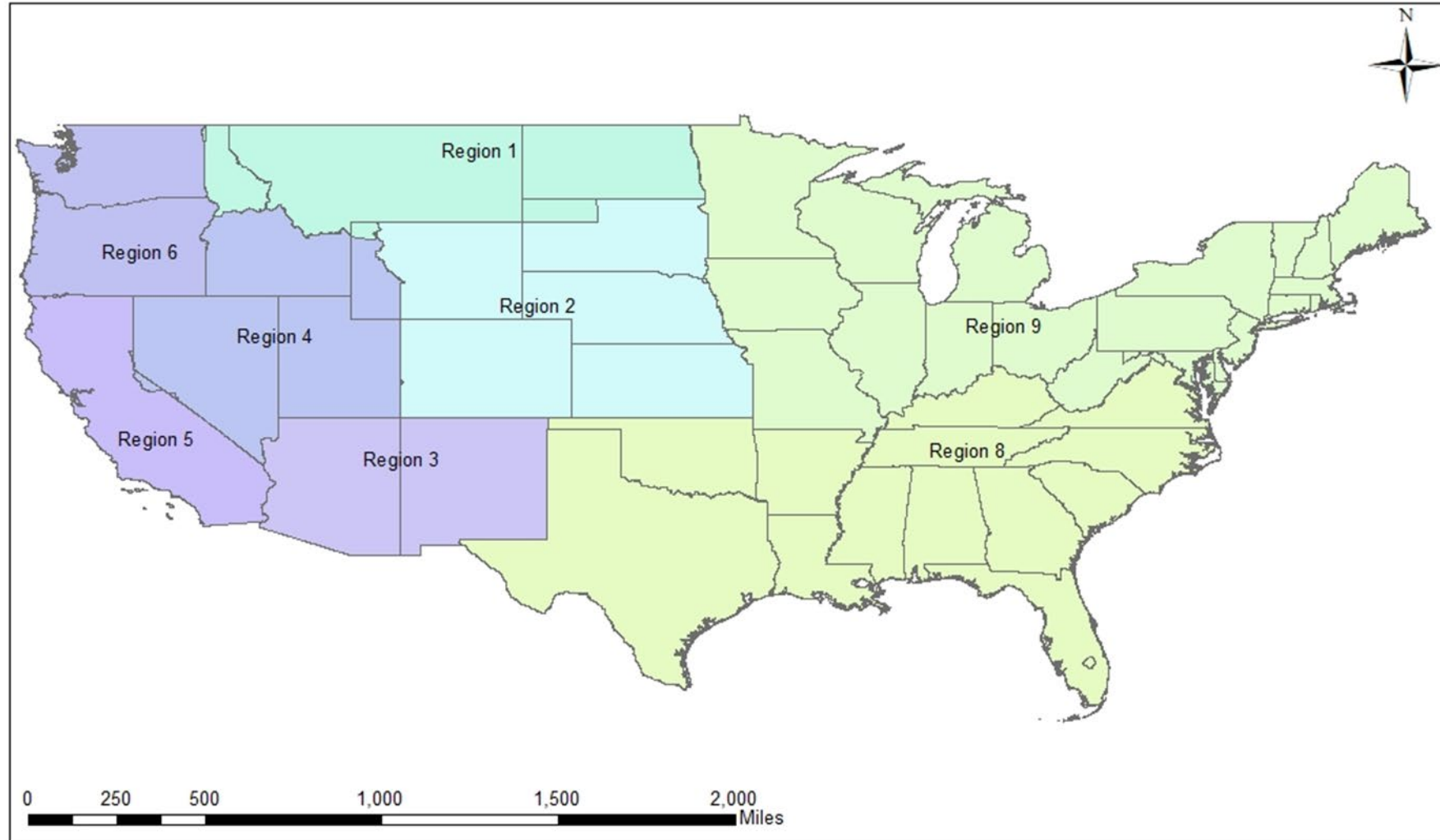
## Legend

Region 1 - Northern	Region 5 - Pacific Southwest
Region 2 - Rocky Mountain	Region 6 - Pacific Northwest
Region 3 - Southwestern	Region 8 - Southern
Region 4 - InterMountain	Region 9 - Eastern

Source: United States  
Department of Agriculture  
NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones



# United States Department of Agriculture Continental U.S. Geogrphic Boundaries



## Legend

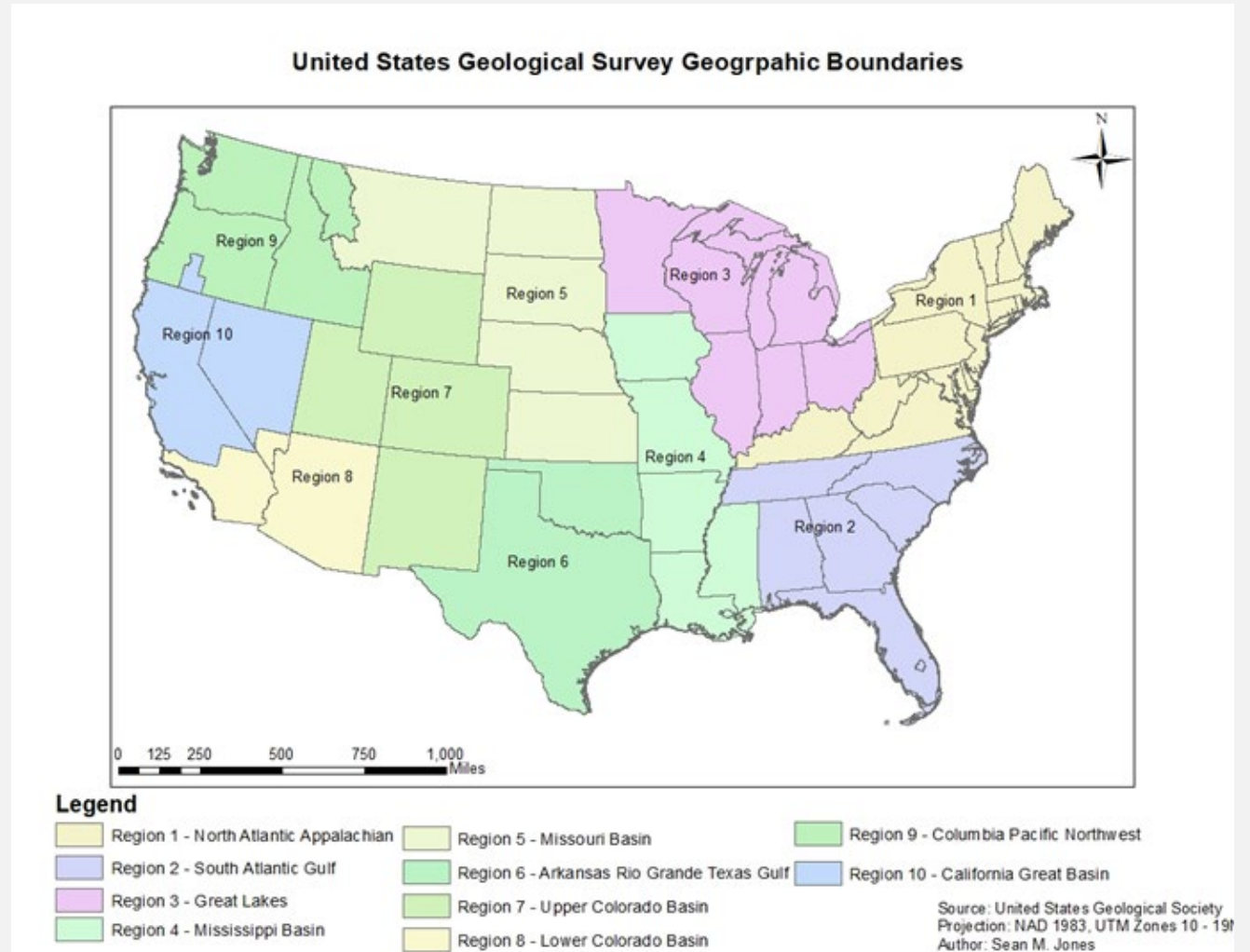
 Region 1 - Northern	 Region 5 - Pacific Southwest
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Source: United States  
Department of Agriculture  
NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones

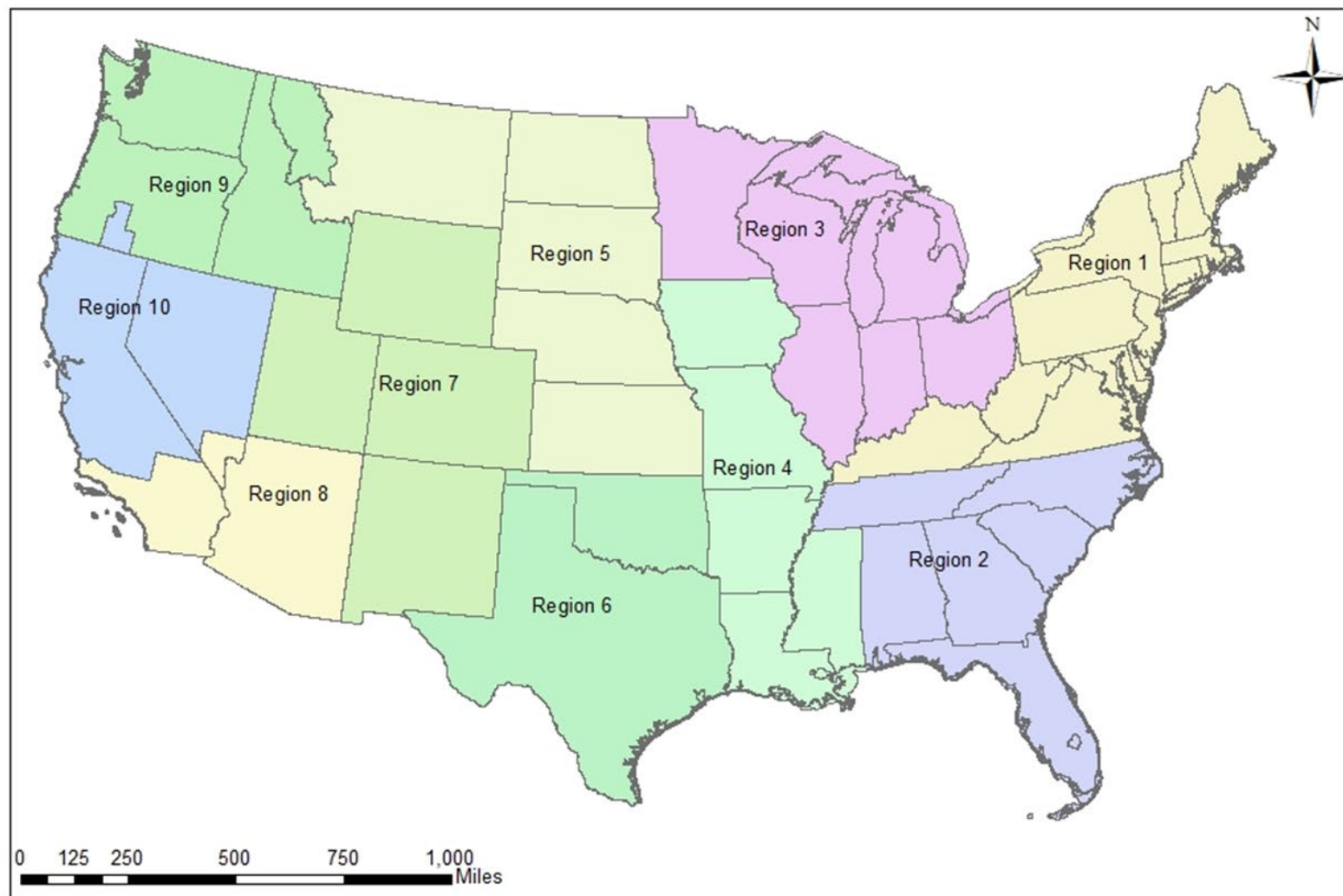


# UNITED STATES GEOLOGICAL SOCIETY

- Although state boundaries are delineated, watersheds are taken into consideration.
- Takes into consideration underlying geology and type of environment.
  - Degrading vs. Aggrading.



## United States Geological Survey Geogrphic Boundaries



### Legend

Region 1 - North Atlantic Appalachian	Region 5 - Missouri Basin	Region 9 - Columbia Pacific Northwest
Region 2 - South Atlantic Gulf	Region 6 - Arkansas Rio Grande Texas Gulf	Region 10 - California Great Basin
Region 3 - Great Lakes	Region 7 - Upper Colorado Basin	
Region 4 - Mississippi Basin	Region 8 - Lower Colorado Basin	

Source: United States Geological Society  
Projection: NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones



# GRAVITY RECOVERY AND CLIMATE EXPERIMENT (GRACE-FO)

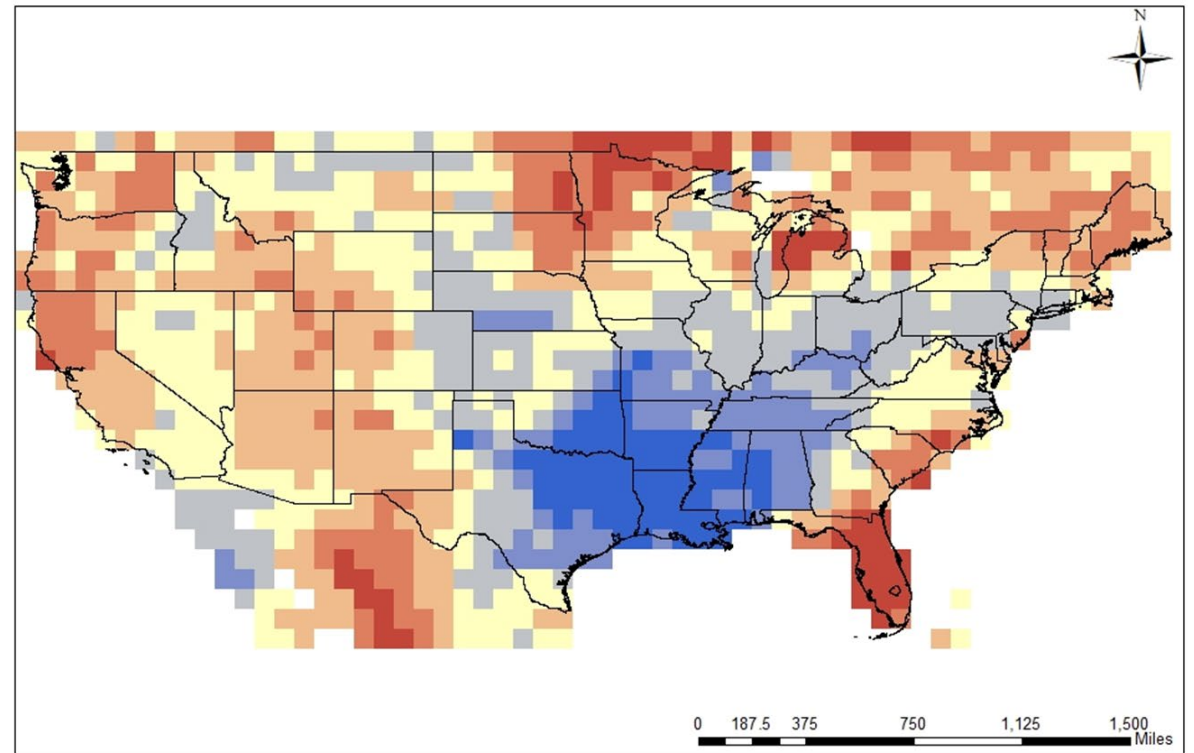
- What is the purpose of GRACE?
- How does it work?
- What does it measure?
- Special considerations?
  - Mass changes
- Limitations?



# DATA

- Sources
  - Imagery
    - NASA
    - ESA
  - Boundaries
    - EPA
    - USGS
    - USDA
    - NOAA

GRACE Continental United States  
June 2021



## Legend

Continental United States Boundaries

**Change in Mean Groundwater  
Height Equivalent (mm)**

-234.8116302 - -133.3379567

-133.3379566 - -88.57015961

-88.5701596 - -55.74044172

-55.74044171 - -22.91072382

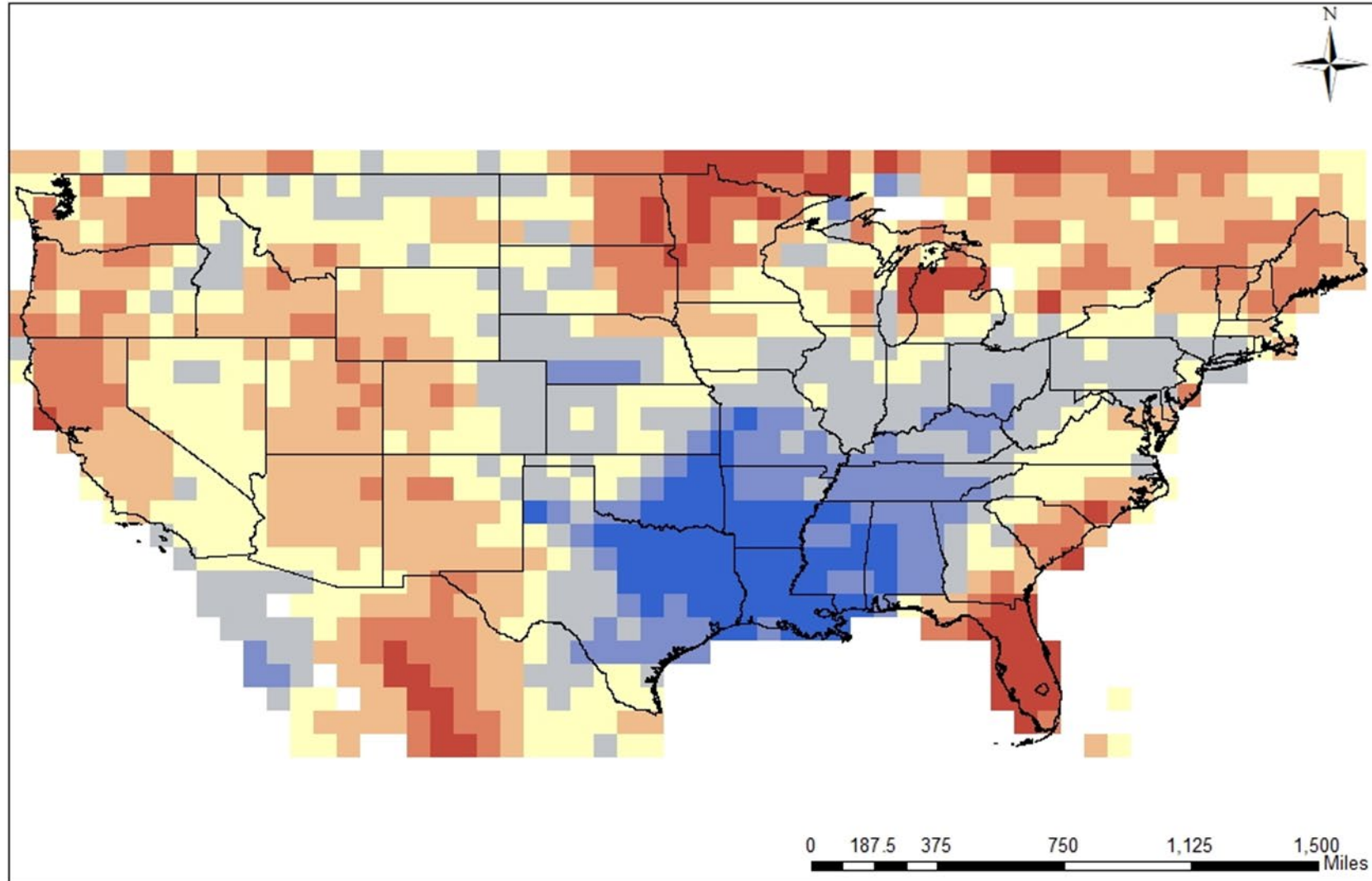
-22.91072381 - 17.3802936

17.38029361 - 66.62487045

66.62487046 - 145.7146454

Source: NASA, ESA, NOAA  
Projection: WGS 1984  
UTM Zones 10-19N  
Author: Sean M. Jones

# GRACE Continental United States June 2021



## Legend

Continental United States Boundaries

**Change in Mean Groundwater  
Height Equivalent (mm)**

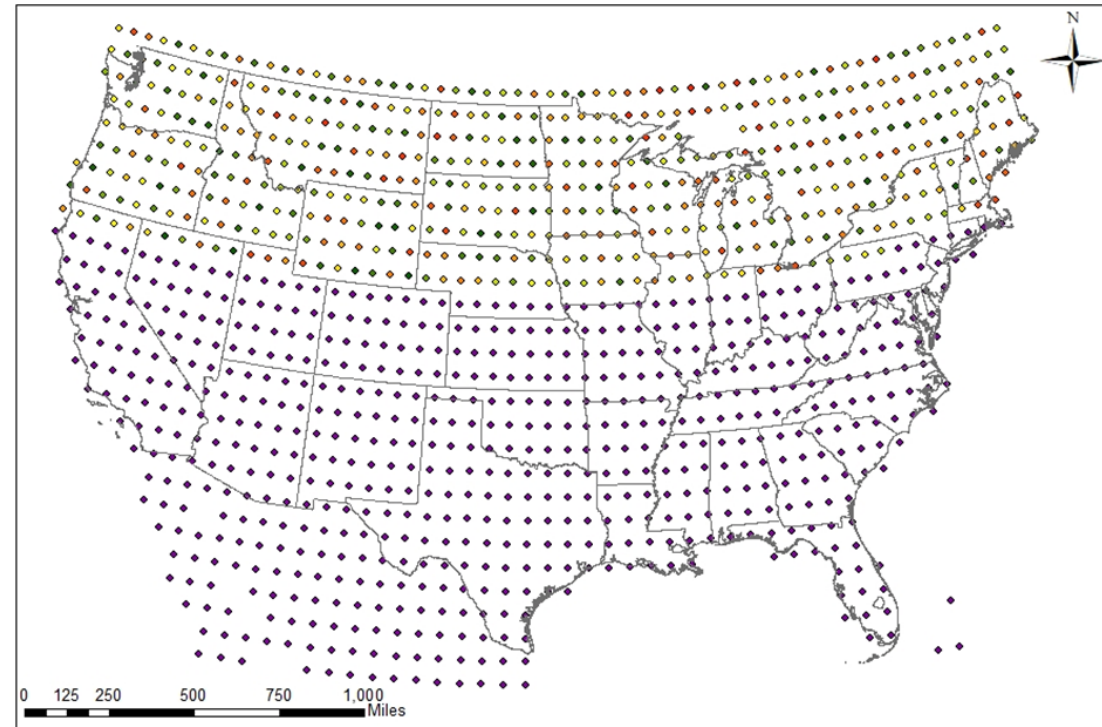


Source: NASA, ESA, NOAA  
Projection: WGS 1984  
UTM Zones 10-19N  
Author: Sean M. Jones

# DATA PROCESSING

- Data was “Clipped”
  - Every month
  - 2019-2021
- Raster to Point
- Point Clipped for each Agency and region
- EPA -288 data tables
- USDA – 288 data tables
- USGS - 360 data tables
  - Over 900 sets of data

## GRACE Raster to Point Conversion



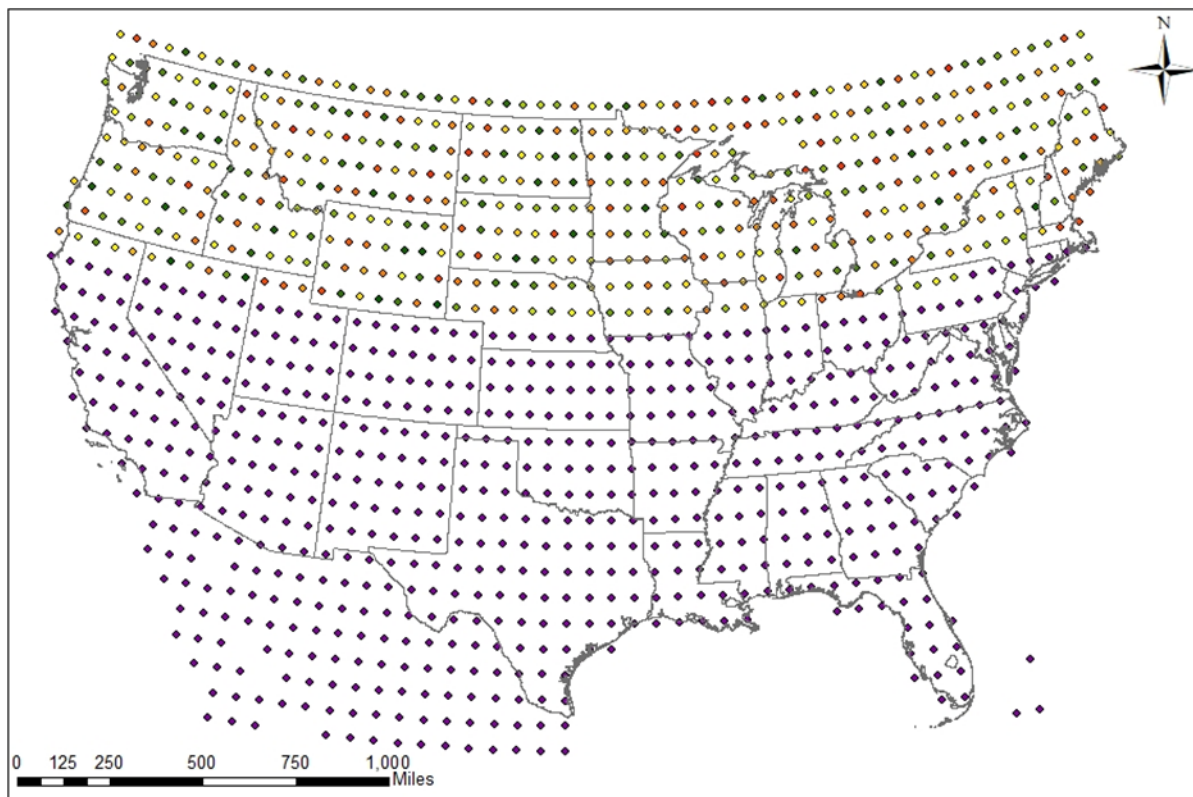
### Legend

- GRACE Raster Converted to Point

Source: United States Geological Society  
Projection: NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones



## GRACE Raster to Point Conversion



### Legend

- ◆ GRACE Raster Converted to Point

Source: United States Geological Society  
Projection: NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones

# DATA PROCESSING

- Each point was converted to Excel
- Regions compiled into one sheet for all 3 years of data
- Data was imported into R studio for statistical analysis
  - Shapiro wilks for normality and plots
- Welch's ANOVA
  - Unequal variances between many of the sets of data
- Games Howell
  - Decrease the chance of a type I error

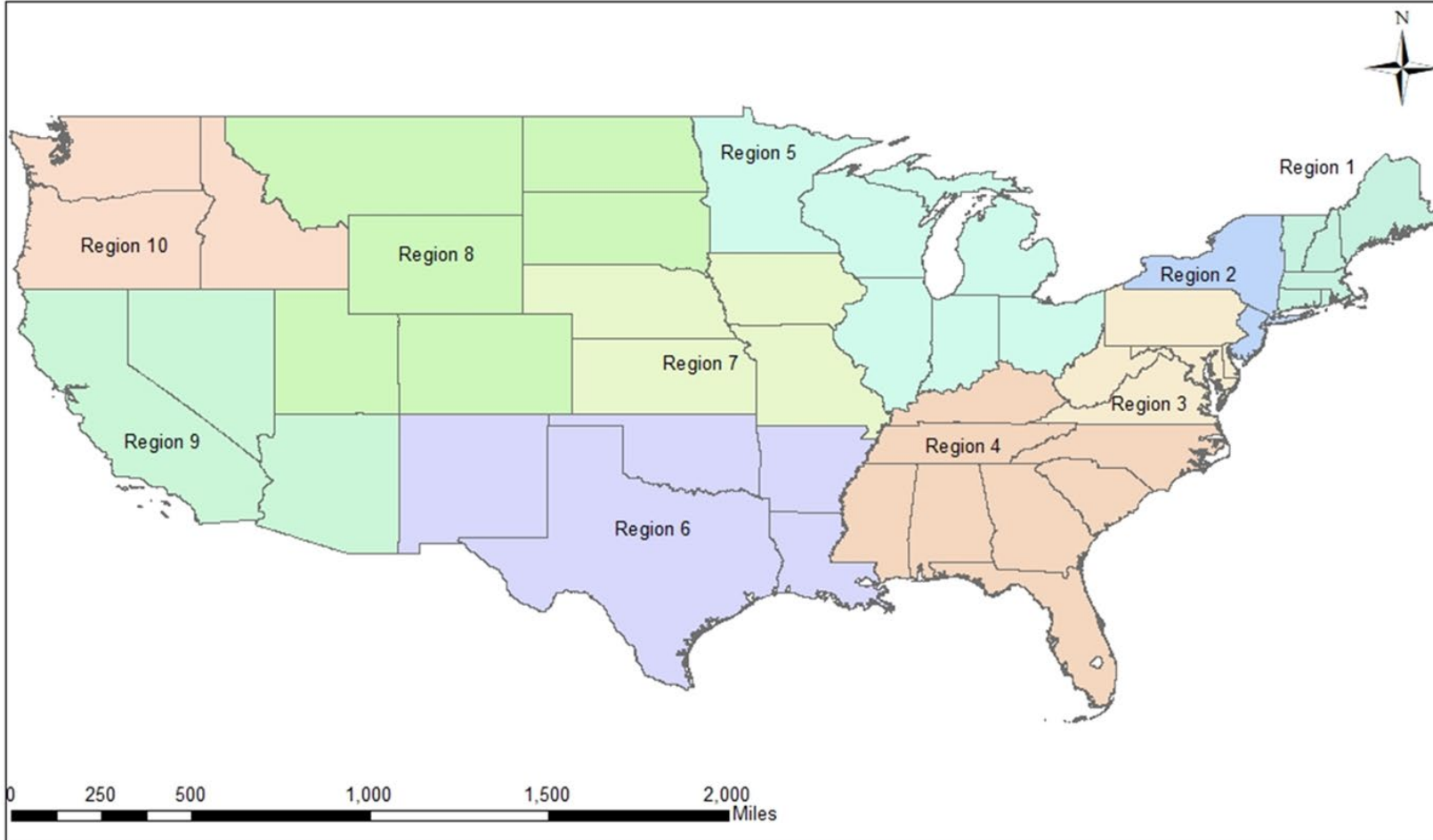
	FID	pointid	grid_code	Reg_Month_Year	Order_of_Entry
24	12	173	127.4048767	06_12_2021	1623
25	13	174	-33.18943024	06_12_2021	1624
26	14	175	27.50722122	06_12_2021	1625
27	15	176	22.41449738	06_12_2021	1626
28	16	177	2.834982157	06_12_2021	1627
29	17	178	-20.94555664	06_12_2021	1628
30	18	229	86.7086792	06_12_2021	1629
31	19	230	111.9589386	06_12_2021	1630
32	20	231	32.86519241	06_12_2021	1631
33	21	232	76.28253174	06_12_2021	1632
34	22	233	11.17042923	06_12_2021	1633
35	23	234	-28.20651245	06_12_2021	1634
36	24	235	-64.39857483	06_12_2021	1635
37	25	286	60.35980988	06_12_2021	1636
38	26	287	14.81422901	06_12_2021	1637
39	27	288	-16.24002647	06_12_2021	1638
40	28	289	-3.433938265	06_12_2021	1639
41	29	290	-51.04116058	06_12_2021	1640
42	30	291	-28.88999558	06_12_2021	1641
43	31	292	-16.50518227	06_12_2021	1642
44	32	343	-8.109808922	06_12_2021	1643
45	33	344	-7.414726734	06_12_2021	1644
46	34	345	-104.8372345	06_12_2021	1645
47	35	346	-33.12137604	06_12_2021	1646
48	36	347	-23.92883492	06_12_2021	1647
49	37	348	-5.187316418	06_12_2021	1648
50	38	349	-15.92987156	06_12_2021	1649
51	39	399	-65.67369843	06_12_2021	1650
52	40	400	-11.70921803	06_12_2021	1651
53	41	401	-21.32728386	06_12_2021	1652
54	42	402	8.364203453	06_12_2021	1653
55	43	403	-10.70177078	06_12_2021	1654
56	44	404	-29.88592911	06_12_2021	1655
57	45	405	-38.63136292	06_12_2021	1656

# EPA RESULTS

Games Howell Results					
Group 1	Group 2	Lower Bound CI	Upper Bound CI	P-Value (adjusted)	Significance
EPA Region 1	EPA Region 10	-10.88246048	14.3553237	1	Not Significant
EPA Region 2	EPA Region 5	-12.8401631	9.804257245	1	Not Significant
EPA Region 2	EPA Region 6	-11.99288636	9.825589447	1	Not Significant
EPA Region 2	EPA Region 7	-10.50111081	12.09217437	1	Not Significant
EPA Region 2	EPA Region 8	-12.09765512	9.683571182	1	Not Significant
EPA Region 2	EPA Region 9	-20.32416733	1.923051557	0.208	Not Significant
EPA Region 3	EPA Region 4	-5.76908169	9.244555243	0.999	Not Significant
EPA Region 5	EPA Region 6	-5.012561445	5.881170384	1	Not Significant
EPA Region 5	EPA Region 7	-3.877497083	8.504466499	0.975	Not Significant
EPA Region 5	EPA Region 8	-5.098264454	5.720086368	1	Not Significant
EPA Region 6	EPA Region 7	-3.514162498	7.272522974	0.985	Not Significant
EPA Region 6	EPA Region 8	-4.596994365	4.35020734	1	Not Significant
EPA Region 7	EPA Region 8	-7.357850435	3.352702934	0.975	Not Significant
EPA Region 1	EPA Region 2	6.956855162	36.23960177	0.00014	***
EPA Region 1	EPA Region 3	36.59601903	60.94002286	0	****
EPA Region 1	EPA Region 4	39.53455074	61.4769647	0	****
EPA Region 1	EPA Region 5	8.872784066	31.28776701	0.000000791	****
EPA Region 1	EPA Region 6	9.724886404	31.30427361	0.00000011	****
EPA Region 1	EPA Region 7	11.21212306	33.57539743	1.49E-08	****
EPA Region 1	EPA Region 8	9.62034519	31.1620278	0.000000128	****
EPA Region 1	EPA Region 9	1.391049801	23.40429135	0.014	*
EPA Region 10	EPA Region 2	7.141931517	32.58166219	0.0000373	****
EPA Region 10	EPA Region 3	37.2675277	56.79565097	0	****
EPA Region 10	EPA Region 4	40.55811763	56.98053459	1.99E-08	****
EPA Region 10	EPA Region 5	9.818201153	26.8694867	4.17E-08	****
EPA Region 10	EPA Region 6	10.81219376	26.74410303	4.46E-09	****
EPA Region 10	EPA Region 7	12.16581722	29.14884005	3.73E-08	****
EPA Region 10	EPA Region 8	10.71447739	26.59503238	3.65E-09	****
EPA Region 10	EPA Region 9	2.402569504	18.91990843	0.002	**
EPA Region 2	EPA Region 3	14.89285899	39.44672597	1.85E-10	****
EPA Region 2	EPA Region 4	17.81892398	39.99613453	0	****
EPA Region 3	EPA Region 5	-36.53689505	-20.83859577	6.16E-11	****
EPA Region 3	EPA Region 6	-35.49154696	-21.01533492	0	****
EPA Region 3	EPA Region 7	-34.18637295	-18.56214845	5.32E-11	****
EPA Region 3	EPA Region 8	-35.58671053	-21.16695837	0	****
EPA Region 3	EPA Region 9	-43.92899062	-28.81171012	1.82E-11	****
EPA Region 4	EPA Region 5	-36.22551967	-24.6254447	1.61E-12	****



**United State Environmental Protection Agency  
Continental U.S. Geogrphic Boundaries**



**Legend**

EPA Region 1	EPA Region 5	EPA Region 9
EPA Region 2	EPA Region 6	EPA Region 10
EPA Region 3	EPA Region 7	
EPA Region 4	EPA Region 8	

Source: United States Environmental Protection Agency  
NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones

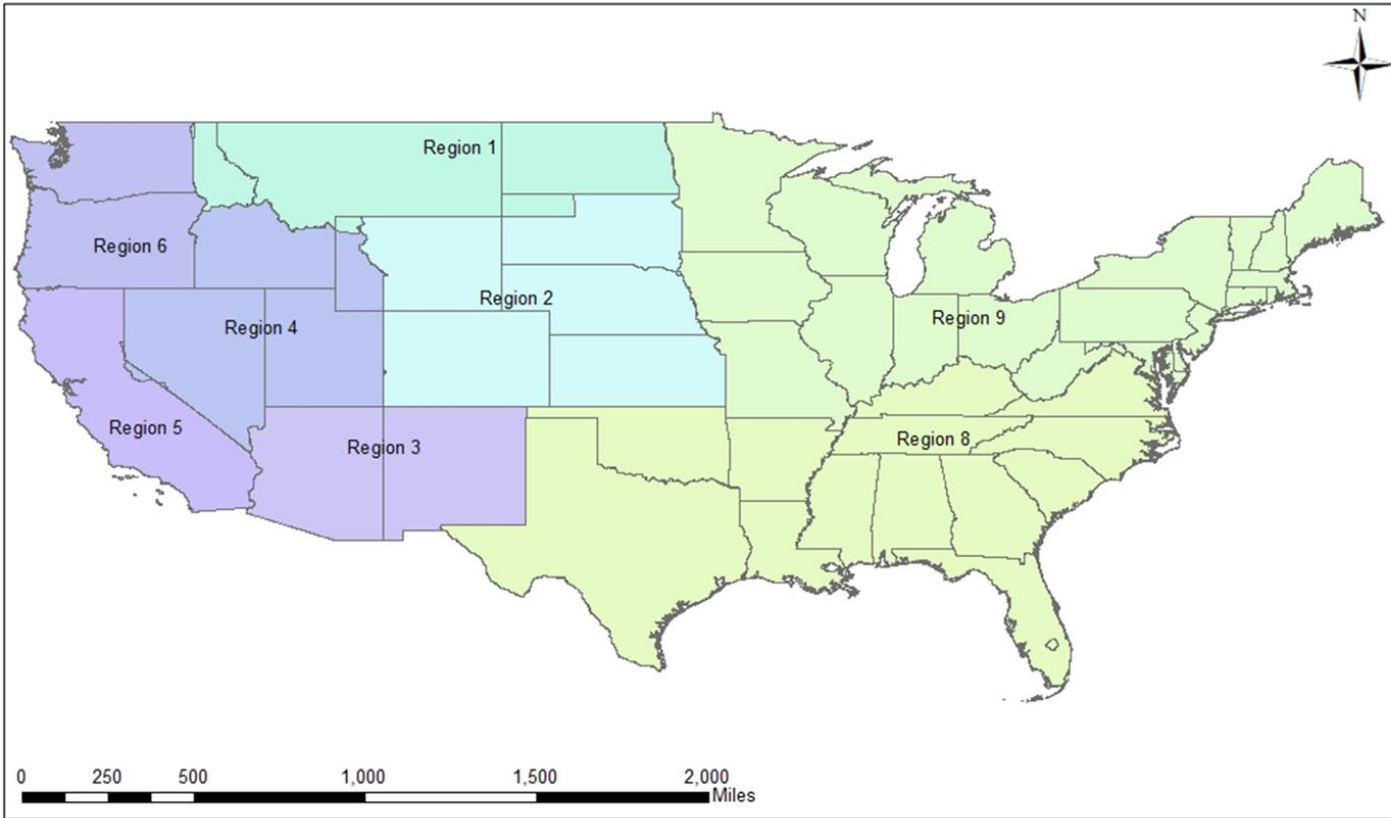
**EPA  
REGIONAL  
COMPARISON**

EPA Comparison of GW Fluctuations Between Regions		
Group 1	Group 2	Significance
EPA Region 1	EPA Region 10	Not Significant
EPA Region 2	EPA Region 5	Not Significant
EPA Region 2	EPA Region 6	Not Significant
EPA Region 2	EPA Region 7	Not Significant
EPA Region 2	EPA Region 8	Not Significant
EPA Region 2	EPA Region 9	Not Significant
EPA Region 3	EPA Region 4	Not Significant
EPA Region 5	EPA Region 6	Not Significant
EPA Region 5	EPA Region 7	Not Significant
EPA Region 5	EPA Region 8	Not Significant
EPA Region 6	EPA Region 7	Not Significant
EPA Region 6	EPA Region 8	Not Significant
EPA Region 7	EPA Region 8	Not Significant

# USDA RESULTS

USDA Comparison of GW Fluctuations Between Regions					
Games Howell Results					
Group 1	Group 2	Lower Bound CI	Upper Bound CI	P-Value (adjusted)	Significance
USDA Region 1	USDA Region 2	-3.153235242	9.663205098	0.786	Not Significant
USDA Region 1	USDA Region 9	-5.709223557	5.591780115	1	Not Significant
USDA Region 2	USDA Region 9	-8.450937674	1.823524376	0.512	Not Significant
USDA Region 4	USDA Region 5	-12.0339676	6.125262488	0.976	Not Significant
USDA Region 1	USDA Region 3	-29.57373553	-17.7551967	0.000000031	****
USDA Region 1	USDA Region 4	-20.99025888	-8.295563458	8.75E-11	****
USDA Region 1	USDA Region 5	-27.01729444	-8.177233011	0.000000453	****
USDA Region 1	USDA Region 6	-44.44863068	-24.21170213	0	****
USDA Region 1	USDA Region 8	8.750838521	19.64041485	4.22E-08	****
USDA Region 2	USDA Region 3	-32.34016467	-21.49873743	0	****
USDA Region 2	USDA Region 4	-23.793219	-12.0025732	0	****
USDA Region 2	USDA Region 5	-29.97448632	-11.73001098	2.11E-10	****
USDA Region 2	USDA Region 6	-47.42696727	-27.7433354	0	****
USDA Region 2	USDA Region 8	6.03064581	15.8506377	4.34E-10	****
USDA Region 3	USDA Region 4	3.672916149	14.37019374	0.00000902	****
USDA Region 3	USDA Region 6	-20.19064591	-1.14075466	0.016	*
USDA Region 3	USDA Region 8	33.6223186	42.097867	0.000000012	****
USDA Region 3	USDA Region 9	19.10664381	28.10484498	2.75E-12	****
USDA Region 4	USDA Region 6	-29.48956872	-9.884941742	0.000000036	****
USDA Region 4	USDA Region 8	24.00821458	33.66886113	0	****
USDA Region 4	USDA Region 9	9.52306871	19.64531019	0	****
USDA Region 5	USDA Region 6	-28.75116722	-4.714638139	0.000654	***
USDA Region 5	USDA Region 8	23.31837207	40.26740874	2.13E-12	****
USDA Region 5	USDA Region 9	8.930640171	26.14644384	2.18E-08	****
USDA Region 6	USDA Region 8	39.28124895	57.77033723	3.24E-11	****
USDA Region 6	USDA Region 9	24.90444162	43.63844774	5.21E-11	****
USDA Region 8	USDA Region 9	-18.12217761	-10.3865192	3.61E-09	****

United States Department of Agriculture  
Continental U.S. Geogrpahic Boundaries



# USDA REGIONAL COMPARISON

**Legend**

- Region 1 - Northern
- Region 2 - Rocky Mountain
- Region 3 - Southwestern
- Region 4 - InterMountain
- Region 5 - Pacific Southwest
- Region 6 - Pacific Northwest
- Region 8 - Southern
- Region 9 - Eastern

Source: United States  
Department of Agriculture  
NAD 1983, UTM Zones 10 - 19N  
Author: Sean M. Jones

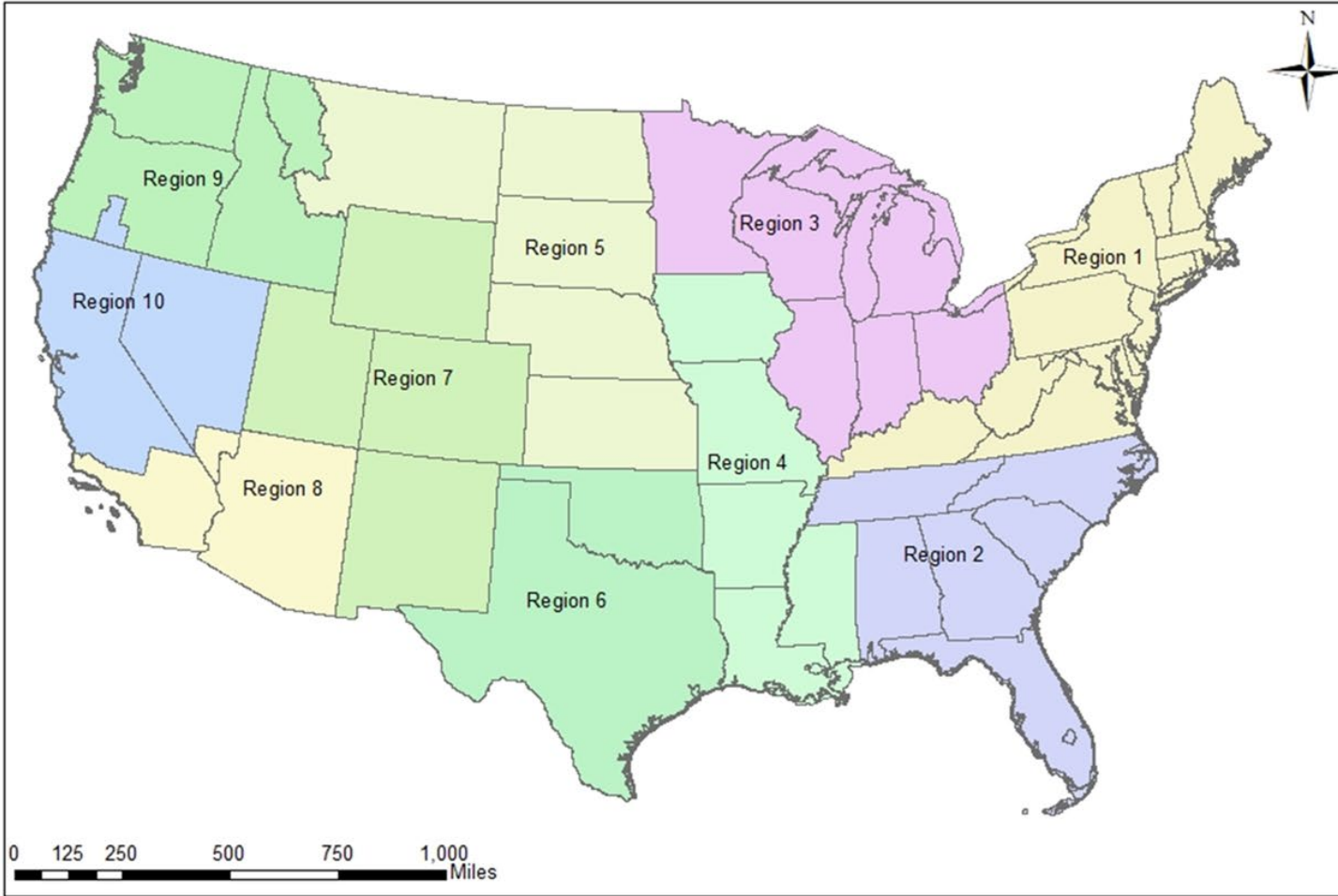
USDA Comparison of GW Fluctuations Between Regions		
Group 1	Group 2	Significance
USDA Region 1	USDA Region 2	Not Significant
USDA Region 1	USDA Region 9	Not Significant
USDA Region 2	USDA Region 9	Not Significant
USDA Region 4	USDA Region 5	Not Significant



# USGS RESULTS

USGS Comparison of GW Fluctuations Between Regions					
Games Howell Results					
Group 1	Group 2	Lower Bound CI	Upper Boun CI	P-Value (adjusted)	Significance
USGS Region 1	USGS Region 10	-10.88246048	14.3553237	1	Not Significant
USGS Region 2	USGS Region 5	-12.8401631	9.804257245	1	Not Significant
USGS Region 2	USGS Region 6	-11.99288636	9.825589447	1	Not Significant
USGS Region 2	USGS Region 7	-10.50111081	12.09217437	1	Not Significant
USGS Region 2	USGS Region 8	-12.09765512	9.683571182	1	Not Significant
USGS Region 2	USGS Region 9	-20.32416733	1.923051557	0.208	Not Significant
USGS Region 3	USGS Region 4	-5.76908169	9.244555243	0.999	Not Significant
USGS Region 5	USGS Region 6	-5.012561445	5.881170384	1	Not Significant
USGS Region 5	USGS Region 7	-3.877497083	8.504466499	0.975	Not Significant
USGS Region 5	USGS Region 8	-5.098264454	5.720086368	1	Not Significant
USGS Region 6	USGS Region 7	-3.514162498	7.272522974	0.985	Not Significant
USGS Region 6	USGS Region 8	-4.596994365	4.35020734	1	Not Significant
USGS Region 7	USGS Region 8	-7.357850435	3.352702934	0.975	Not Significant
USGS Region 1	USGS Region 2	6.956855162	36.23960177	0.00014	***
USGS Region 1	USGS Region 3	36.59601903	60.94002286	0	****
USGS Region 1	USGS Region 4	39.53455074	61.4769647	0	****
USGS Region 1	USGS Region 5	8.872784066	31.28776701	0.00000791	****
USGS Region 1	USGS Region 6	9.724886404	31.30427361	0.00000011	****
USGS Region 1	USGS Region 7	11.21212306	33.57539743	1.49E-08	****
USGS Region 1	USGS Region 8	9.62034519	31.1620278	0.000000128	****
USGS Region 1	USGS Region 9	1.391049801	23.40429135	0.014	*
USGS Region 10	USGS Region 2	7.141931517	32.58166219	0.0000373	****
USGS Region 10	USGS Region 3	37.2675277	56.79565097	0	****
USGS Region 10	USGS Region 4	40.55811763	56.98053459	1.99E-08	****
USGS Region 10	USGS Region 5	9.818201153	26.8694867	4.17E-08	****
USGS Region 10	USGS Region 6	10.81219376	26.74410303	4.46E-09	****
USGS Region 10	USGS Region 7	12.16581722	29.14884005	3.73E-08	****
USGS Region 10	USGS Region 8	10.71447739	26.59503238	3.65E-09	****
USGS Region 10	USGS Region 9	2.402569504	18.91990843	0.002	**
USGS Region 2	USGS Region 3	14.89285899	39.44672597	1.85E-10	****
USGS Region 2	USGS Region 4	17.81892398	39.99613453	0	****
USGS Region 3	USGS Region 5	-36.53689505	-20.83859577	6.16E-11	****
USGS Region 3	USGS Region 6	-35.49154696	-21.01533492	0	****
USGS Region 3	USGS Region 7	-34.18637295	-18.56214845	5.32E-11	****
USGS Region 3	USGS Region 8	-35.58671053	-21.16695837	0	****
USGS Region 3	USGS Region 9	-43.92899062	-28.81171012	1.82E-11	****
USGS Region 4	USGS Region 5	-36.22551967	-24.6254447	1.61E-12	****
USGS Region 4	USGS Region 6	-34.93054953	-25.0518059	1.72E-11	****
USGS Region 4	USGS Region 7	-33.8617847	-22.36221026	0	****
USGS Region 4	USGS Region 8	-35.01232325	-25.21681921	3.41E-11	****
USGS Region 4	USGS Region 9	-43.50747942	-32.70869487	9.25E-12	****
USGS Region 5	USGS Region 9	-13.54971199	-1.815497931	0.001	***
USGS Region 6	USGS Region 9	-13.13490724	-3.098911626	0.0000139	****
USGS Region 7	USGS Region 9	-15.81352318	-4.178656162	0.00000249	****
USGS Region 8	USGS Region 9	-12.97055565	-3.01647619	0.0000168	****

# United States Geological Survey Geogrphic Boundaries



## Legend

- Region 1 - North Atlantic Appalachian
- Region 2 - South Atlantic Gulf
- Region 3 - Great Lakes
- Region 4 - Mississippi Basin
- Region 5 - Missouri Basin
- Region 6 - Arkansas Rio Grande Texas Gulf
- Region 7 - Upper Colorado Basin
- Region 8 - Lower Colorado Basin
- Region 9 - Columbia Pacific Northwest
- Region 10 - California Great Basin

Source: United States Geological Society  
 Projection: NAD 1983, UTM Zones 10 - 19N  
 Author: Sean M. Jones

# USGS REGIONAL COMPARISON

USGS Comparison of GW Fluctuations Between Regions		
Group 1	Group 2	Significance
USGS Region 1	USGS Region 10	Not Significant
USGS Region 2	USGS Region 5	Not Significant
USGS Region 2	USGS Region 6	Not Significant
USGS Region 2	USGS Region 7	Not Significant
USGS Region 2	USGS Region 8	Not Significant
USGS Region 2	USGS Region 9	Not Significant
USGS Region 3	USGS Region 4	Not Significant
USGS Region 5	USGS Region 6	Not Significant
USGS Region 5	USGS Region 7	Not Significant
USGS Region 5	USGS Region 8	Not Significant
USGS Region 6	USGS Region 7	Not Significant
USGS Region 6	USGS Region 8	Not Significant
USGS Region 7	USGS Region 8	Not Significant

## CONCLUSIONS

- There are similar Ground Water trends in regions that would not be expected.
- Groundwater is highly variable between regions, and further investigation is required to accurately assess the complexity of impacts to these systems.

## FUTURE RESEARCH

- Groundwater policies by state.
- Landcover classification.
  - Percentage of surface area as agriculture
  - What types of agriculture
- Population
- Industry



# SOURCES

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