

**SCALING IN GEOTHERMAL
HEAT PUMP SYSTEMS**

Prepared For:

**U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, ID 83401**

Contract No. DE-FG07-90ID 13040

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July 1999

DISCLAIMER STATEMENT

This report was prepared with the support of the U.S. Department of Energy (DOE Grant No. DE-FG07-90ID 13040). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the view of DOE.

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SCALING IN GEOTHERMAL HEAT PUMP SYSTEMS

INTRODUCTION

Water quality is a frequently overlooked issue in the application of geothermal heat pump (GHP) systems. When considered at all, is often viewed as a problem unique to open loop systems. In residential open loop applications water is supplied directly to the heat pump's refrigerant-to-water heat exchanger. If the water has a tendency to be scale forming, fouling of the heat exchanger may occur. This fouling reduces the effectiveness of the heat exchanger and compromises the performance of the heat pump. Water quality is also a consideration for closed loop systems. In the closed loop system, the concern is not the main refrigerant to water heat exchanger but the desuperheater. Water is circulated through the desuperheater and back to the main hot water heater to provide a portion of the domestic hot water heating needs. Again scale formation in this heat exchanger will reduce the contribution of the desuperheater makes to the domestic hot water heating load. In large commercial systems, the groundwater is isolated from the building loop using a plate-and-frame heat exchanger. This eliminates the potential for scaling in the heat pump units. In addition, it reduces the maximum temperature to which the groundwater is exposed, thus reducing scaling potential.

In most cases, the formation of scale is a slow process occurring over months or years. As a result the impact of the reduced heat pump or desuperheater performance on the utility bill is gradual. This slow erosion of the savings the system would otherwise produce may be imperceptible to the system owner. The object of the work reported here was to identify areas of the country where water quality is such that scale may occur. With this information installers and system owners can plan for the regular maintenance that may be necessary to address the scaling and preserve system performance.

In the residential sector, closed loop GHP's tend to be installed in homes in the upper cost end of the market. Since these homes would likely be equipped with a water softener in hard water areas, the potential for scaling in these instances would be substantially eliminated.

WATER CHEMISTRY AND SCALING

Depending upon it's specific chemistry, water can promote scaling, corrosion or both. Scaling, according to the Water Quality Association, is the number one water quality issue in the US. Scale can be formed from a variety of dissolved chemical species but two reliable indicators are hardness and alkalinity. Calcium carbonate is the most common form of scale deposition attributable to ground water used in residential GHP systems.

Total hardness is primarily a measure of the calcium and magnesium salts in water. In addition, other minor contributing components to hardness can be aluminum, manganese, iron and zinc (Carrier, 1965). Two types of hardness are generally recognized: carbonate (sometimes referred to as temporary hardness) and non-carbonate hardness. Carbonate hardness, depending upon the

nature of the water is composed of calcium or magnesium carbonates and bicarbonates. It is this form of hardness that contributes most to scale formation. Non-carbonate hardness is normally a small component of the total hardness and is characterized by much higher solubility. As a result it's role in scale formation is generally negligible.

Water hardness is classified according to a somewhat subjective criteria that varies from reference to reference. Table 1 provides a common interpretation. Scaling problems typically occur above levels of 100 ppm hardness.

Table 1
Water Hardness Classification (Carrier, 1965)

<u>Hardness (as ppm CaCO₃)¹</u>	<u>Classification</u>
<15	Very soft
15 to 50	Soft
50 to 100	Medium hard
100 to 200	Hard
>200	Very Hard

1. Hardness is sometimes expressed in units of grains per gallon(gpg). To convert gpg to ppm as CaCO₃ multiply by 17.1.

Calcium hardness is a key parameter in evaluating scale formation. It generally constitutes 70% or more of the total hardness in water. For worst case evaluations or in the absence of sufficient information, calcium hardness can be considered equal to total hardness. If a calcium ion value is available from a water chemistry analysis, calcium hardness (as CaCO₃) can be calculated by multiplying the calcium ion value by 2.5.

Alkalinity is a measure of a water's ability to neutralize acid. Like hardness it is usually expressed as ppm CaCO₃. In the range of normal ground water chemistry, alkalinity is the result primarily of the bicarbonate content of the water. At pH values of greater than 8.3 carbonate and hydroxide can also contribute to alkalinity. Two measures of alkalinity are of interest: Methyl Orange ("M" alkalinity or total alkalinity) and Phenolphthalien ("P"alkalinity). Since P alkalinity measures that portion of the alkalinity effective at very high pH, the M alkalinity is the value of interest in evaluating scale potential.

A relationship between hardness and alkalinity exists as follows:

If M alkalinity is greater than total hardness, all hardness is due to carbonates and bicarbonates.

If M alkalinity is less than total hardness, carbonate hardness = M alkalinity
non-carbonate hardness = total hardness - M alkalinity.

In order to evaluate the general character (scale forming or corrosive) of a particular water sample it is necessary to know the total dissolved solids (TDS), pH and temperature in addition to the calcium hardness and the M alkalinity.

Total dissolved solids is a general indication of the quality of a water source. As TDS increases water quality problems are more likely to occur. Whether these problems are on the corrosion or scaling end of the spectrum is dependant upon other indicators. Federal drinking water standards call for a limit of 1000 ppm in waters used for municipal water supplies though this is not directly health related.

The pH value of most ground waters is in the range of 5.0 on the acid end of the spectrum to 9.0 on the alkaline end. Scaling problems are common at pH value above 7.5.

Two indices commonly used in the water treatment industry to evaluate the nature of a water source are the Langelier Saturation Index (LSI or Saturation index) and the Ryznar Stability Index (RSI or Stability index). In both cases these indices are based upon a calculated pH of saturation for calcium carbonate (pH_s). The pH_s value is then used in conjunction with the water's actual pH to calculate the value of the index as follows:

$$LSI = pH - pH_s$$

$$RSI = 2pH_s - pH$$

Evaluation of the saturation index is as indicated in Table 2. The stability index (table 3) produces a slightly different value numerically but is interpreted in a similar fashion.

Table 2
Interpretation of the Langelier Saturation Index (Carrier, 1965)

<u>LSI Index Value</u>	<u>Indication</u>
2.0	Scale forming but non corrosive
0.5	Slightly scale forming and corrosive
0.0	Balanced but pitting corrosion possible
-0.5	Slightly corrosive but non-scale forming
-2.0	Serious corrosion

Table 3
Interpretation of the Ryznar Stability Index (Carrier, 1965)

<u>RSI Index Value</u>	<u>Indication</u>
4.0 - 5.0	Heavy scale
5.0 - 6.0	Light scale
6.0 - 7.0	Little scale or corrosion
7.0 - 7.5	Corrosion significant
7.5 - 9.0	Heavy corrosion
> 9.0	Corrosion intolerable

It is important to point out that the accuracy of the RSI and LSI is much greater as a predictor of scaling than of corrosion. This results from the fact that both methods are based upon the saturation of calcium carbonate. The assumption implicit in the calculations is that if the calcium

carbonate content exceeds the level that can be maintained in solution, scale will occur. At lower pH corrosion will occur. In terms of general corrosion in systems constructed of primarily ferrous materials, this is a valid assumption for corrosion. In heat pump systems where the materials are more likely to be copper or cupro-nickel there are other chemical species that can cause serious corrosion that are not accounted for in the RSI/LSI calculations. These would include hydrogen sulphide (H₂S) and ammonia (NH₄) among others. As a result for GHP systems, the RSI/LSI indices should be used as scaling rather than corrosion predictors.

Calculation of the value for pHs can be done using the nomograph found in various references (ASHRAE, 1995; Carrier, 1965) or through the use of the following equation:

$$\text{pHs} = (9.3 + A + B) - (C + D) \quad (\text{Edstrom, 1998})$$

Where:

A = (log(TDS) - 1)/10	TDS in ppm
B = (-13.12 log(°C + 273)) + 34.55	Temperature in °C
C = (log (calcium hardness)) - 0.4	Ca hardness in ppm (as CaCO ₃)
D = log(M alkalinity)	M Alk in ppm as (CaCO ₃)

Example:

pH = 8.2, TDS = 500 ppm, calcium hardness = 165 ppm as CaCO₃, Alkalinity = 100 ppm as Ca CO₃, temperature = 55 °F (12.8 °C)

$$\begin{aligned} A &= (\log (500) - 1)/10 = 0.17 \\ B &= (-13.12 \log(12.8+273)) + 34.55 = 2.33 \\ C &= \log 165 - 0.4 = 1.82 \\ D &= \log 100 = 2.0 \end{aligned}$$

$$\text{pHs} = (9.3 + 0.17 + 2.33) - (1.82 + 2.0) = 7.98$$

$$\begin{aligned} \text{LSI} &= 8.2 - 7.98 = 0.202 \text{ (balanced)} \\ \text{RSI} &= 2(7.98) - 8.2 = 7.76 \text{ (heavy corrosion)} \end{aligned}$$

Same water at 150 °F

$$\begin{aligned} \text{LSI} &= 1.2 \text{ (scale forming)} \\ \text{RSI} &= 5.8 \text{ (light scale)} \end{aligned}$$

It is apparent from this example that the temperature at which the calculation is made has considerable impact upon the results. The water chemistry above is non scaling to corrosive at the temperature at which it would be delivered from the well. If exposed to higher temperature, it would deposit scale. For heat pump applications this is an important consideration.

Figure 1 is a plot of scale deposit at various temperatures for a water containing 170 ppm hardness. The relationship between temperature and scaling is clearly demonstrated.

Lime Deposited vs Temperature and Use @ 170 ppm

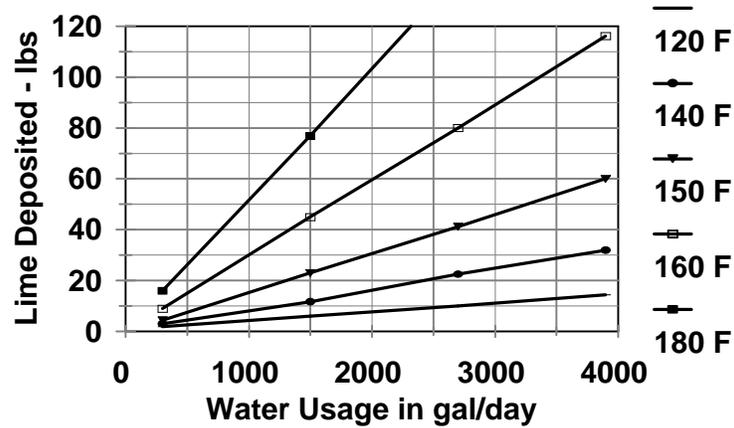


Figure 1 (ASHRAE,1995)

Figure 2 presents a plot of LSI vs pH for a collection of 260 water samples (Carrier, 1965) from across the US. It is apparent that serious scale problems (LSI > 1) are unlikely at pH values less than 7.5.

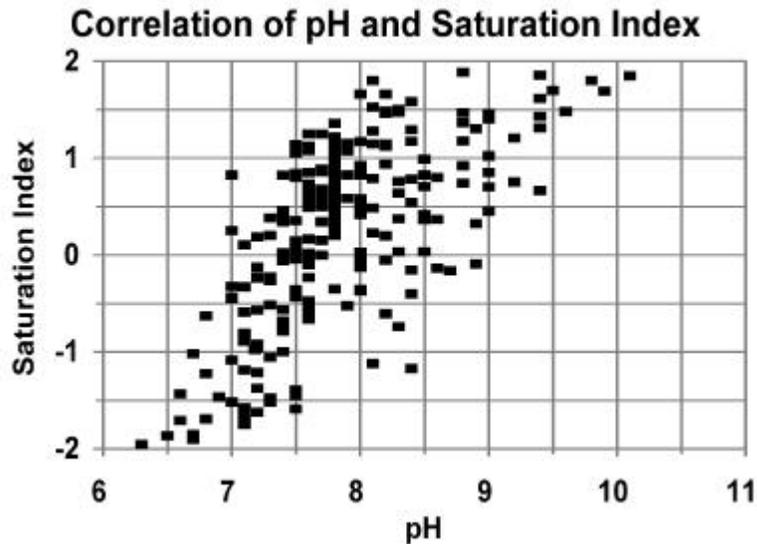


Figure 2.

Figure 3 presents a plot of LSI vs hardness for the same group of samples. It is equally clear from this data that serious scale problems are unlikely at water hardness values below 100 ppm. In addition, hardness values above 200 ppm suggest the potential for serious scaling. In developing the individual state maps of scaling potential, these data were used to establish the thresholds for scaling potential.

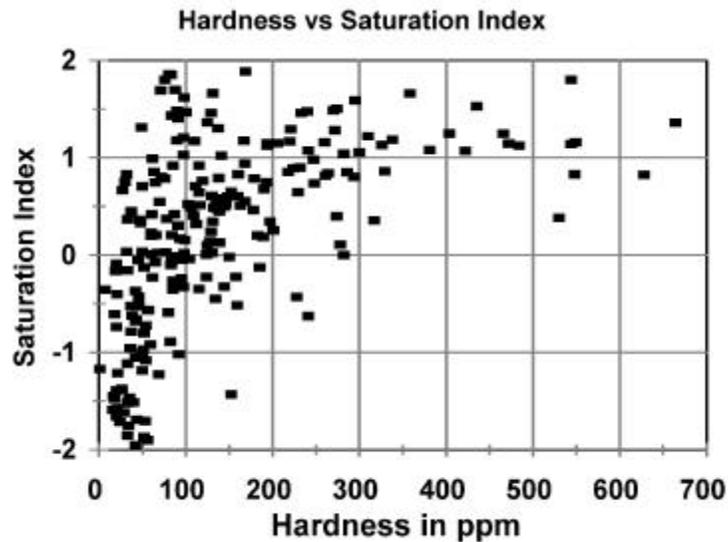


Figure 3.

SCALING IN HEAT PUMP APPLICATIONS

Scaling is a phenomenon that can impact the performance of both open and closed loop heat pump systems. In closed loop systems, the ground loop and main refrigerant to water heat exchanger do not present a problem. Even if the system is filled with a water of high scaling potential, the small volume of water contained would limit the degree of scaling that could result. The situation in the desuperheater (if used) is quite different. With the large throughput of water and exposure to the highest temperatures in the refrigeration cycle, the desuperheater provides optimum conditions for the formation of scale given a water with a scaling chemistry.

In some cases, desuperheaters in installations with very hard water have become completely plugged by scale buildup rendering them inoperable. Unfortunately, in most cases this has occurred without the owner's awareness of the problem. This results from the sequence of operation for desuperheaters. Basically, the desuperheater is intended to provide only a portion of the domestic hot water heating needs of the residence. Heat is available to be recovered when the heat pump is operating to produce space heating or cooling. When the heat pump is not operating, the domestic hot water heater meets the water heating requirements. As the formation

of scale slowly reduces the capacity of the desuperheater, the domestic hot water heater simply picks up the difference. The gradual erosion of savings may proceed unnoticed by the homeowner.

For open loop systems, the same situation exists in the desuperheater as described above. In addition, the main refrigerant to water heat exchanger is also exposed to the well water. Depending upon the specific water chemistry, scaling could occur in both the heating and cooling modes but the cooling mode would be the more susceptible due to the higher temperatures involved.

Figure 4, modified from data in Carrier, 1965 illustrates the impact of scale formation on the performance of a heat pump operating in the cooling mode with 55 °F entering water at 2 gpm/ton. With just .03" of scale on the heat exchanger surface the heat pump power consumption is 19% higher than with a clean surface.

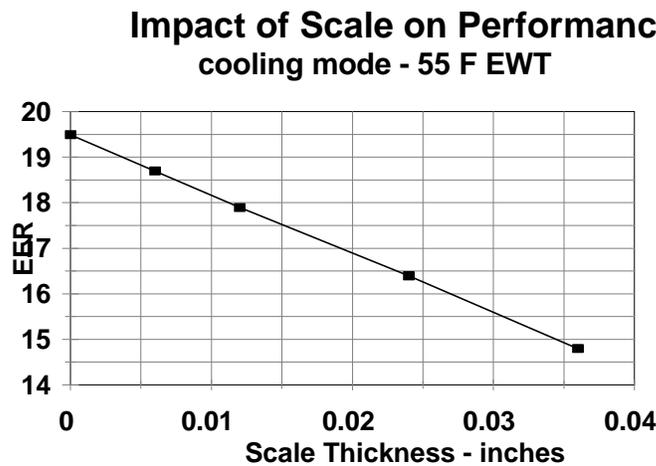


Figure 4.

In large commercial systems, the groundwater is isolated from the building loop using a plate-and-frame heat exchanger. This eliminates the potential for scaling in the heat pump units. In addition, it reduces the maximum temperature to which the groundwater is exposed. In applications in which the groundwater is supplied directly to the heat pump unit, the water encounters surface temperatures as high as 160°F in the hot gas inlet area. By contrast, in a system using an isolation heat exchanger, the maximum water temperature encountered would be in the range of 90°F. Since scaling is a partially temperature driven phenomenon, the use of the isolation heat exchanger is more than simply a strategy of moving the scaling from the heat pumps to the plate heat exchanger. Due to the difference in exposure temperatures, it reduces the propensity for scale formation of a given water chemistry relative to that encountered in systems where the water is used directly.

PREDICTING SCALE FORMATION

The goal of this work was to produce a series of maps indicating the regions of the US in which the potential for scaling in heat pump heat exchangers. Little data is available that offers a comprehensive evaluation of individual aquifer water chemistry. To characterize aquifers in terms of a national scope, it is necessary to focus on a single parameter in order to acquire data of a uniform level of accuracy and resolution. For purposes of this work, hardness was chosen as the parameter upon which to base the indication of scale potential.

As discussed earlier, to make a qualitative determination of scaling potential (using LSI or RSI), it is necessary to know the calcium hardness, M alkalinity, TDS, pH and temperature. Of these, temperature is known as far as what would be encountered in a heat pump, pH is easily measured in the field without the necessity of a lab test and TDS tends to mirror hardness in terms of concentration (high hardness accompanies high TDS). Alkalinity is helpful in characterizing the type of hardness (carbonate or non carbonate) and whether or not it is of the variety that will cause scaling but for a first order indication of potential it can be assumed that all the hardness is carbonate. As a result the key parameter is hardness.

Hardness has been quantified and mapped on a national basis by others (Pettyjohn and others, 1979; Moody and others, 1988 and USGS, 1995) in the past. This data forms the basis for the maps developed under this work. For each state a map was developed with hardness of the principal groundwater aquifer indicated as one of three levels: <100 ppm white, 100 ppm to 200 ppm gray, and >200 ppm dark gray. These three concentrations are indicative of areas in which there would be little concern as to scaling and no particular precautions are necessary, areas where scaling could occur given suitable conditions and areas in which some degree of scaling is likely to occur.

In areas of moderate concern (gray) a field test of the pH would be advisable. If the results of the test indicate a pH of 8.0 or above it would be useful to gather the necessary data to calculate the values for RSI and LSI.

For areas of likely scaling (dark gray) it would be advisable to monitor the performance of the heat pump particularly in regions with high cooling requirements and/or where a desuperheater is used in the absence of a water softener. If periodic tests (of power consumption and refrigerant system pressures - standard tests made by service technicians) indicate that scale is occurring it will be necessary to remove this scale from the heat exchanger (and desuperheater if one is used). This can be done by circulating a weak acid solution through the heat pump heat exchanger for a short period to dissolve the scale.

The following section contains maps produced for each of the states indicating hardness contours for the three levels of concentration mentioned above. It is important to point out that the data used addresses only the principal ground water aquifer. In many areas, there is more than one aquifer used for water wells. In addition the data is appropriate only to those applications using a

private water well. For homes connected to a municipal water system, it is likely that some form of treatment is provided to address very hard water.

REFERENCES

Carrier Air Conditioning Company, 1965. Handbook of Air Conditioning System Design. McGraw-Hill Books. New York.

US Geological Survey, 1995. Ground Water Atlas of the United States. United States Department of the Interior. Washington DC

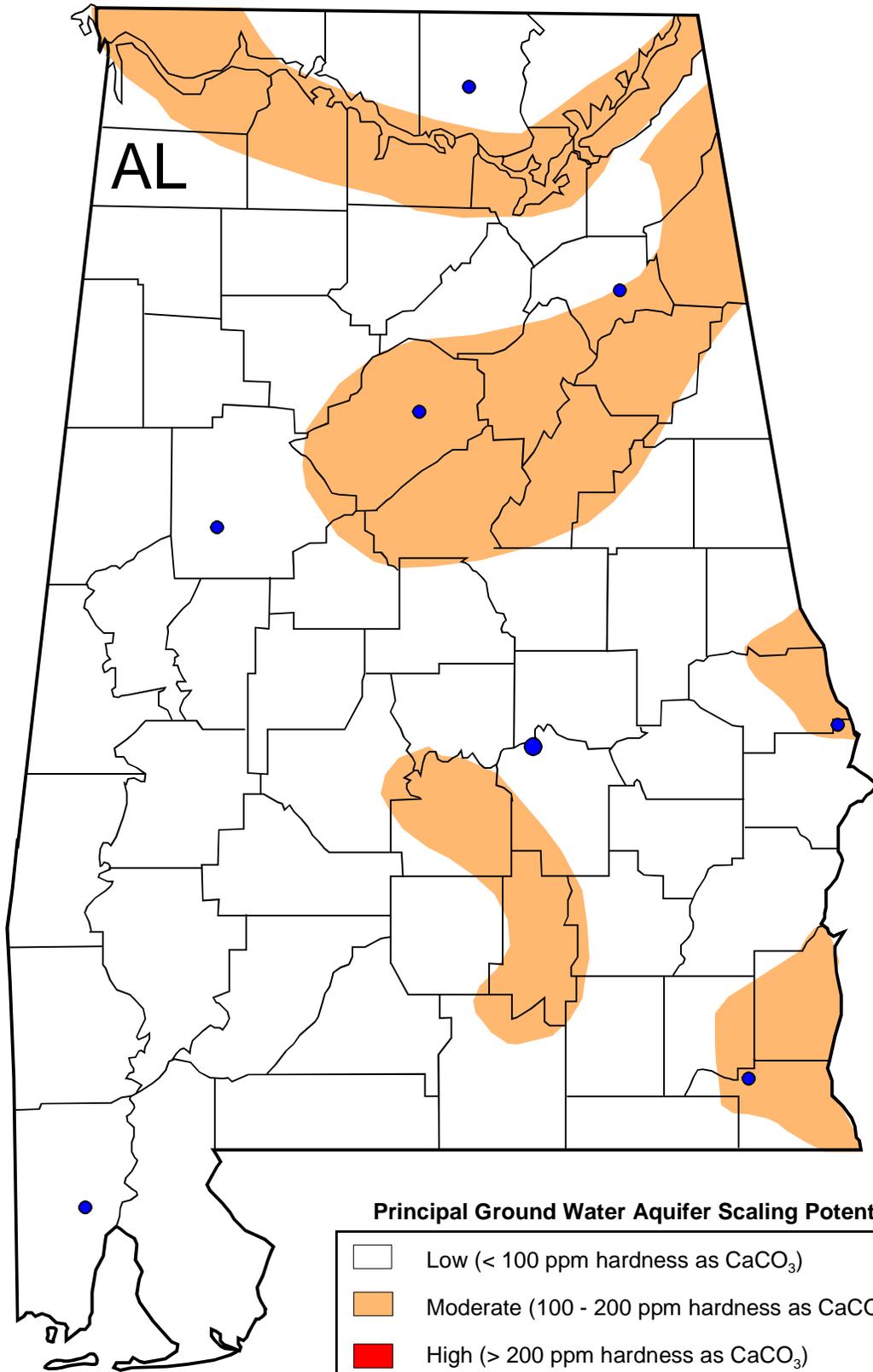
Pettyjohn, WA, Studlick, JRJ, Bain, RC, Lehr, JH, 1979. A Ground-Water Quality Atlas of the United States. National Demonstration Water Project/National Water Well Association. Westerville OH

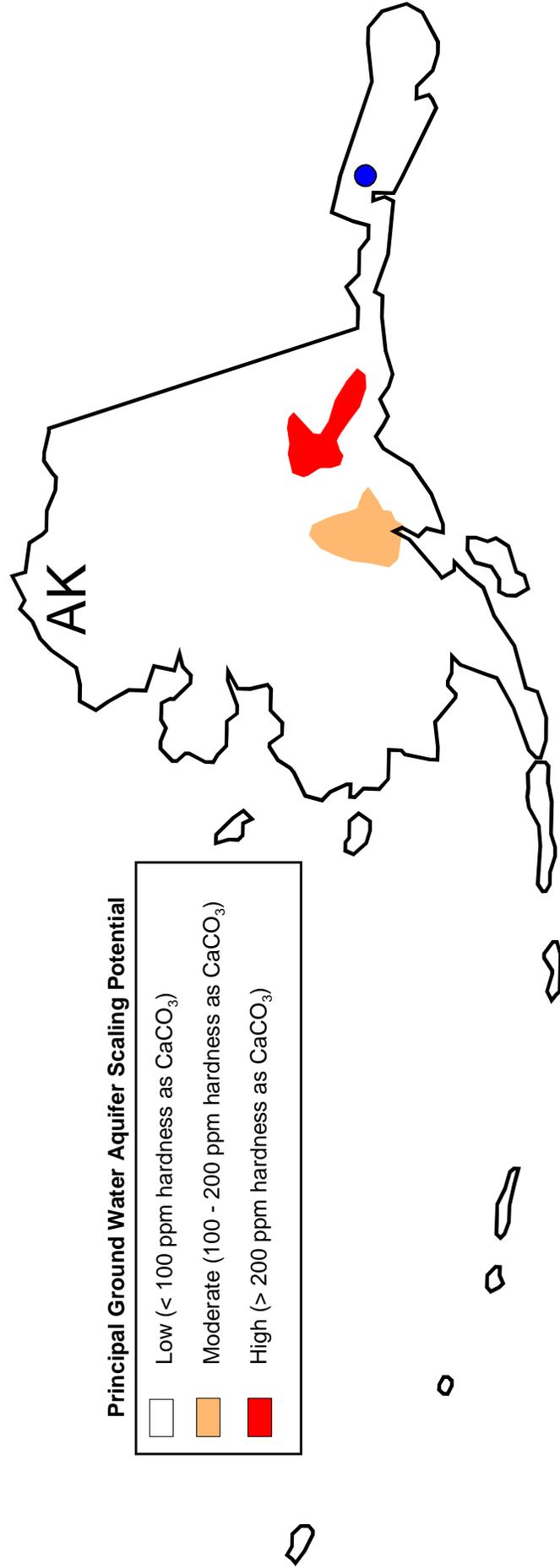
Moody, DW; Carr, J; Chase, EB; Paulson, RW; 1988. National Water Summary 1986-Hydrologic Events and Ground-Water Quality. United States Geologic Survey Water Supply Paper 2325. US Government Printing Office. Washington DC

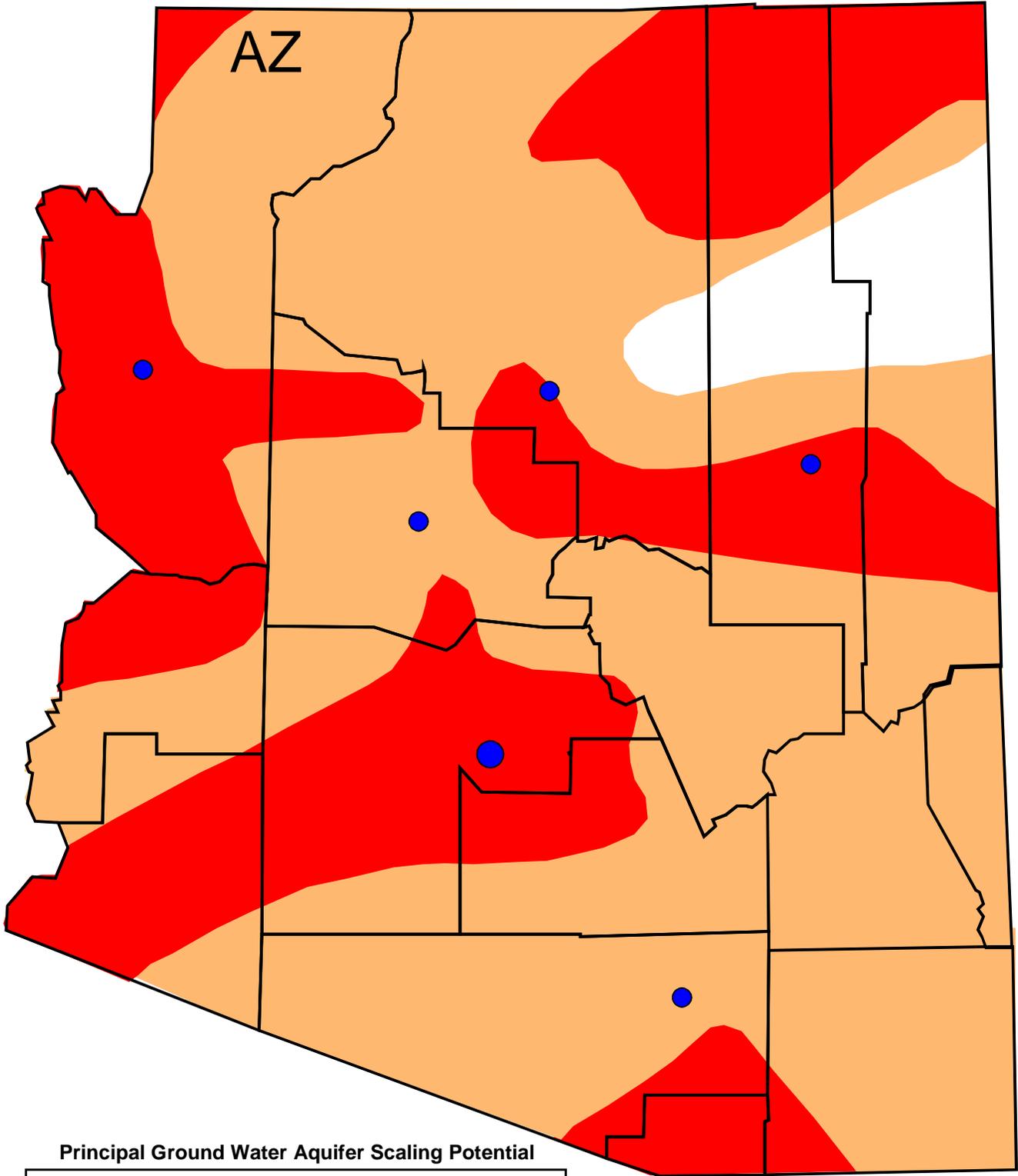
Edstrom Industries, 1998. Scale Forming Tendency of Water. Internet website www.edstrom.com/lab/bulletins/mi4710.thm.

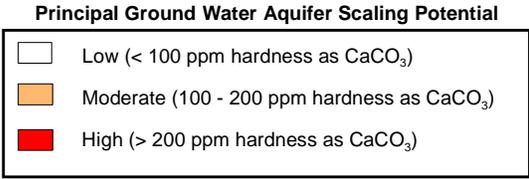
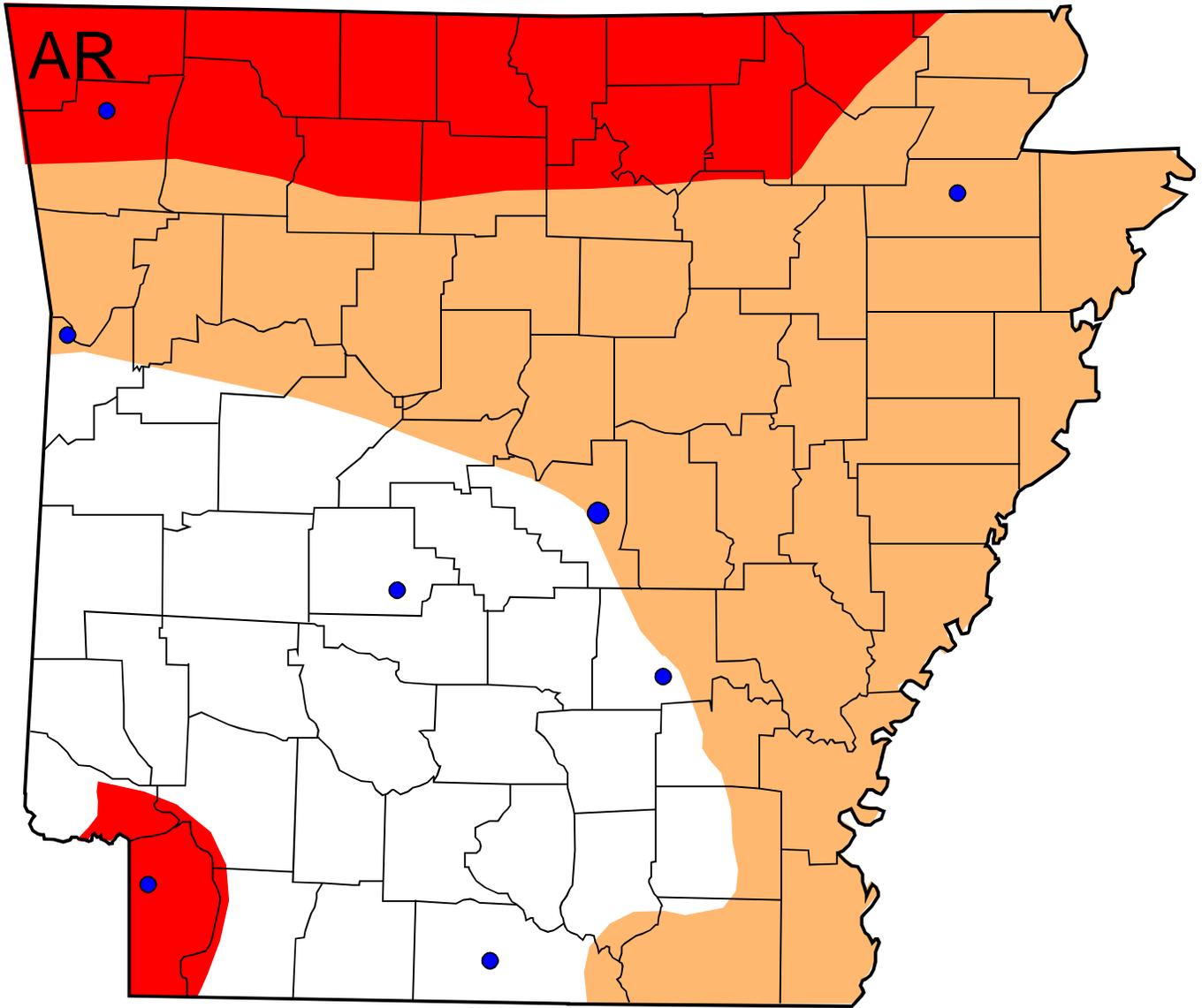
ASHRAE, 1995. Chapter 44 - Corrosion Control and Water Treatment, Handbook of HVAC Applications. American Society of heating refrigeration and Air conditioning Engineers, Atlanta, GA.

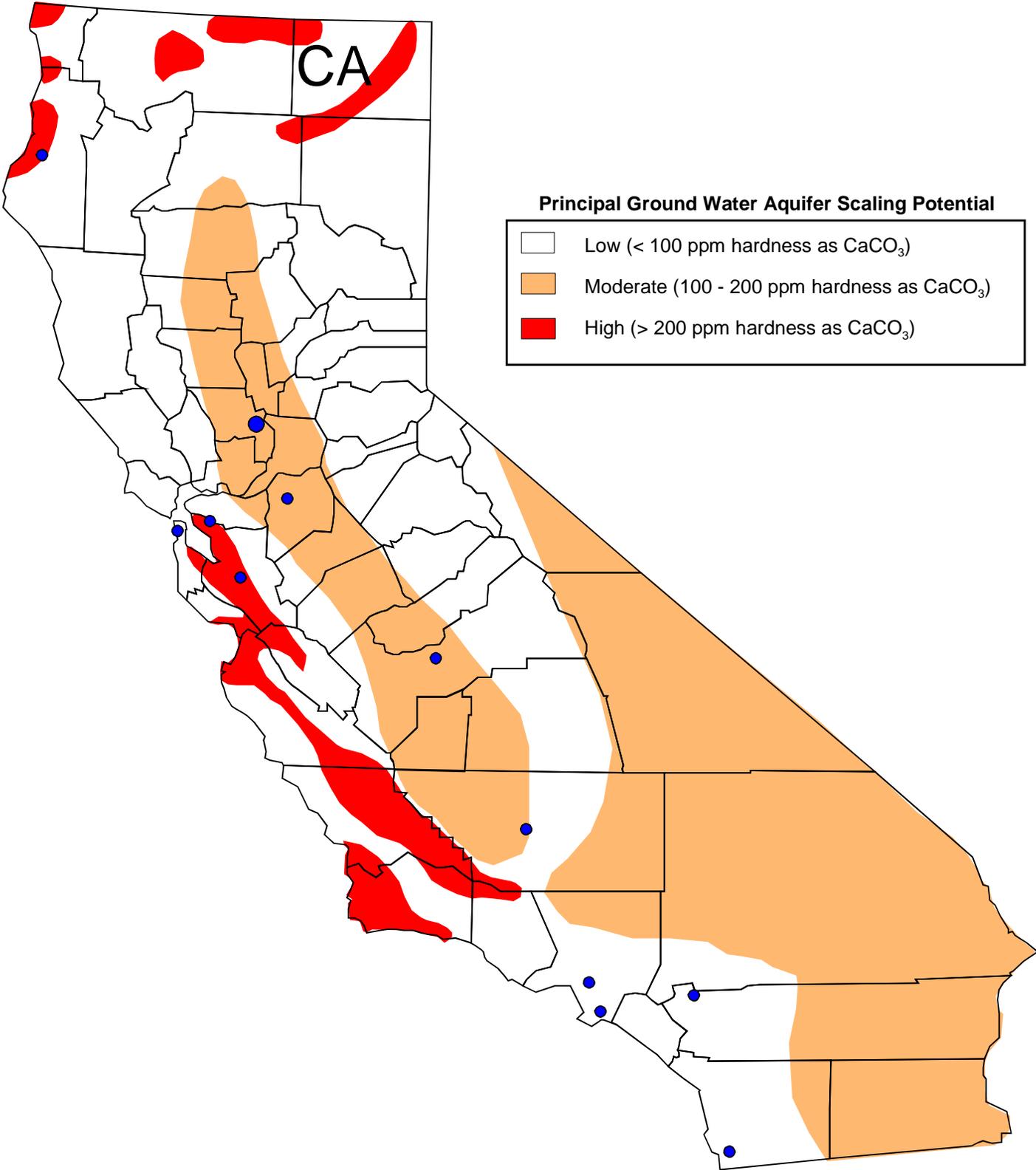
APPENDIX
STATE MAPS

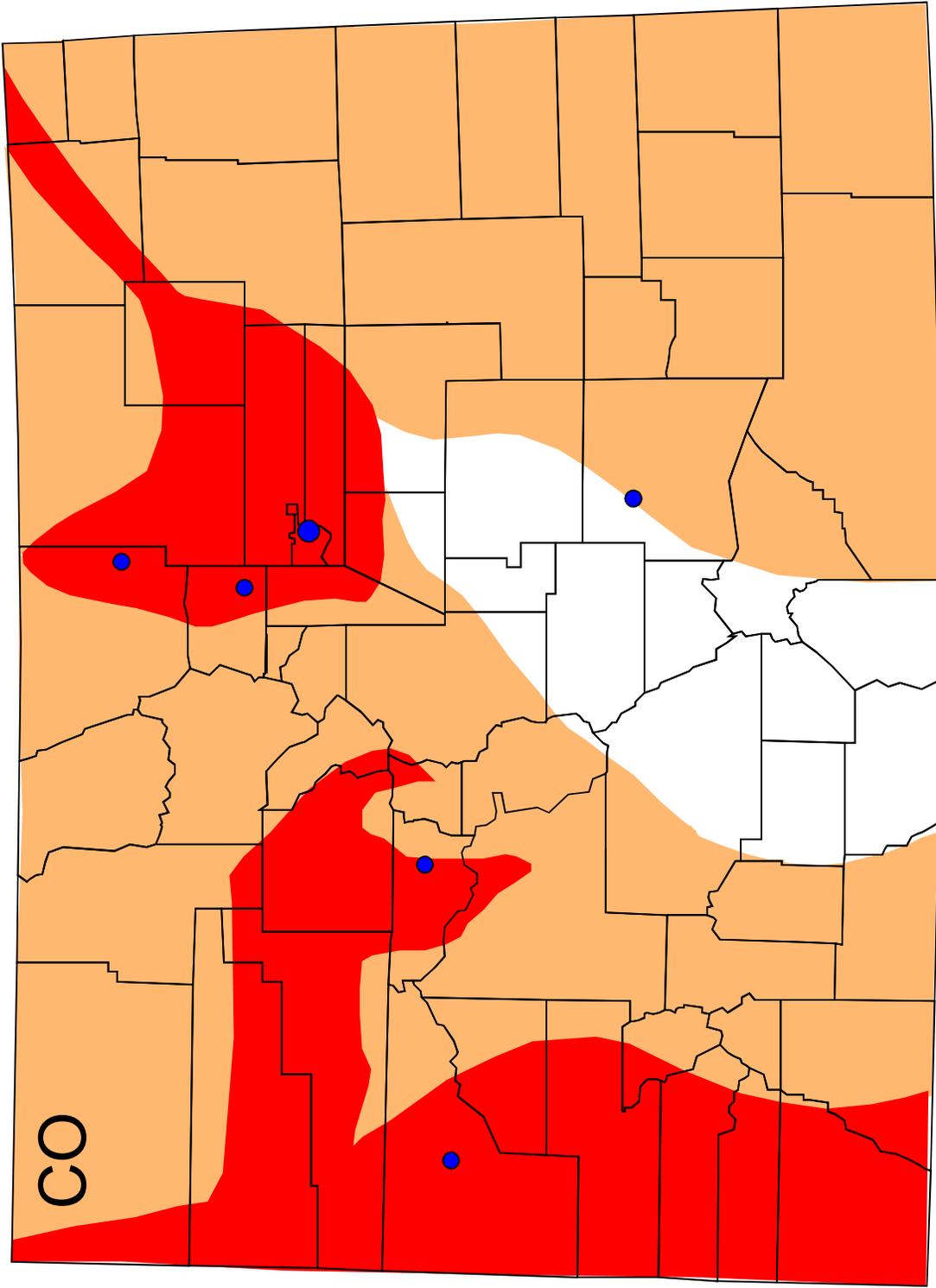




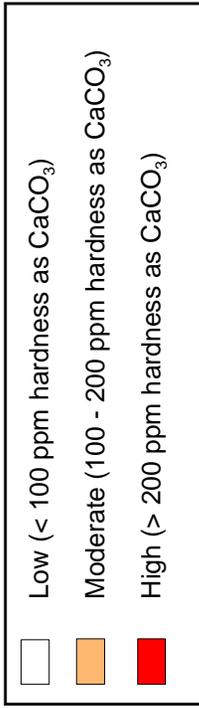


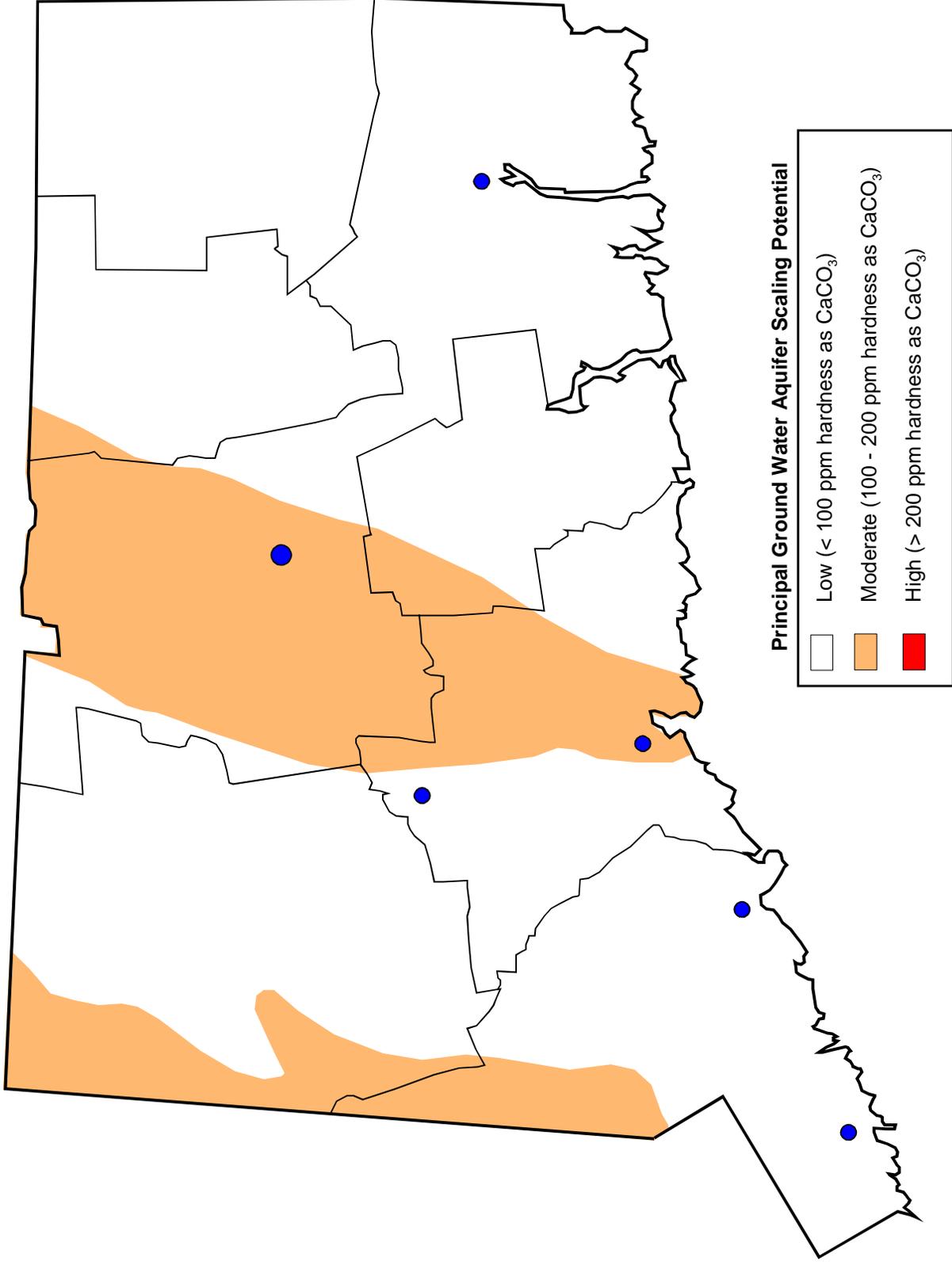


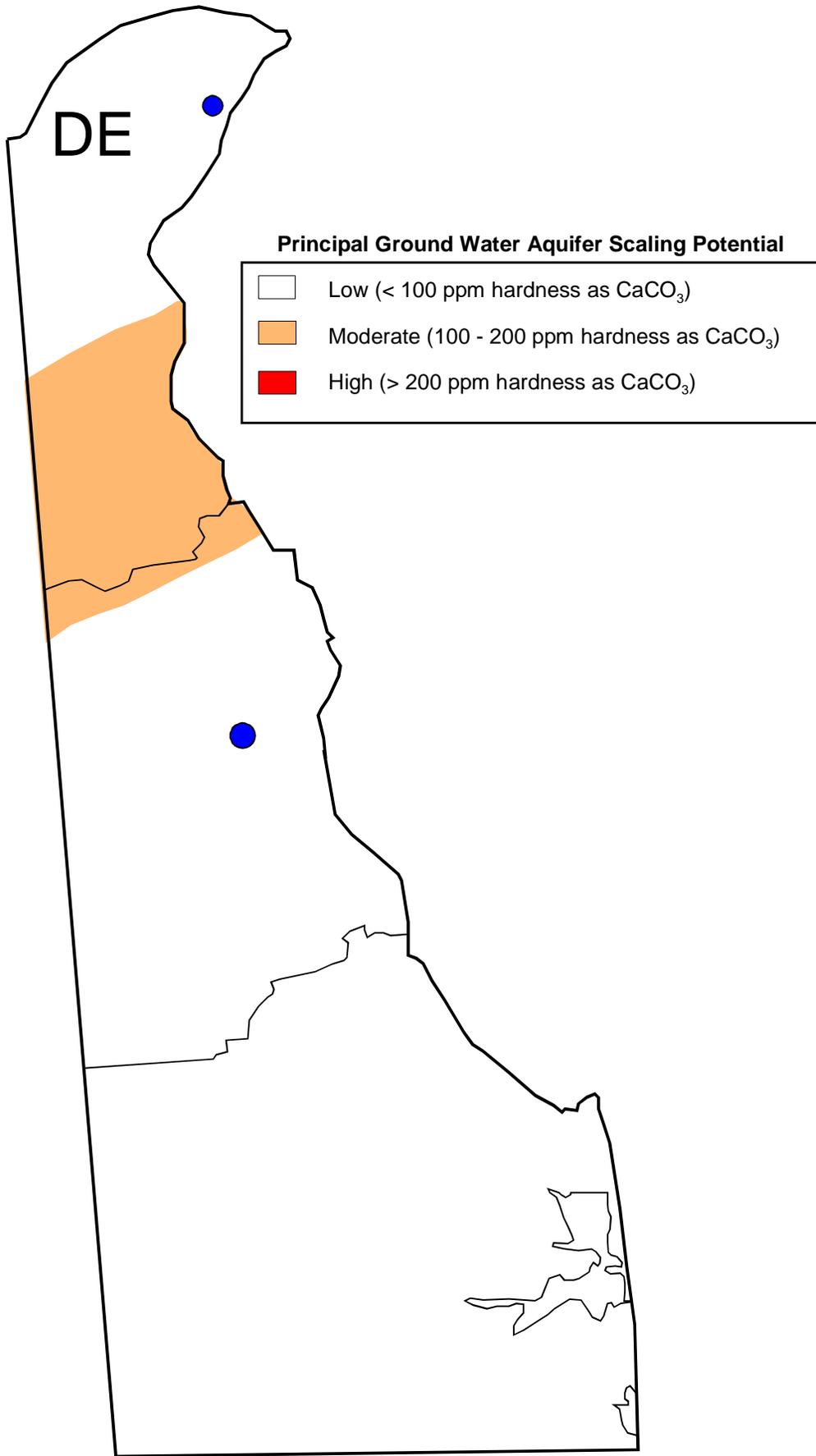


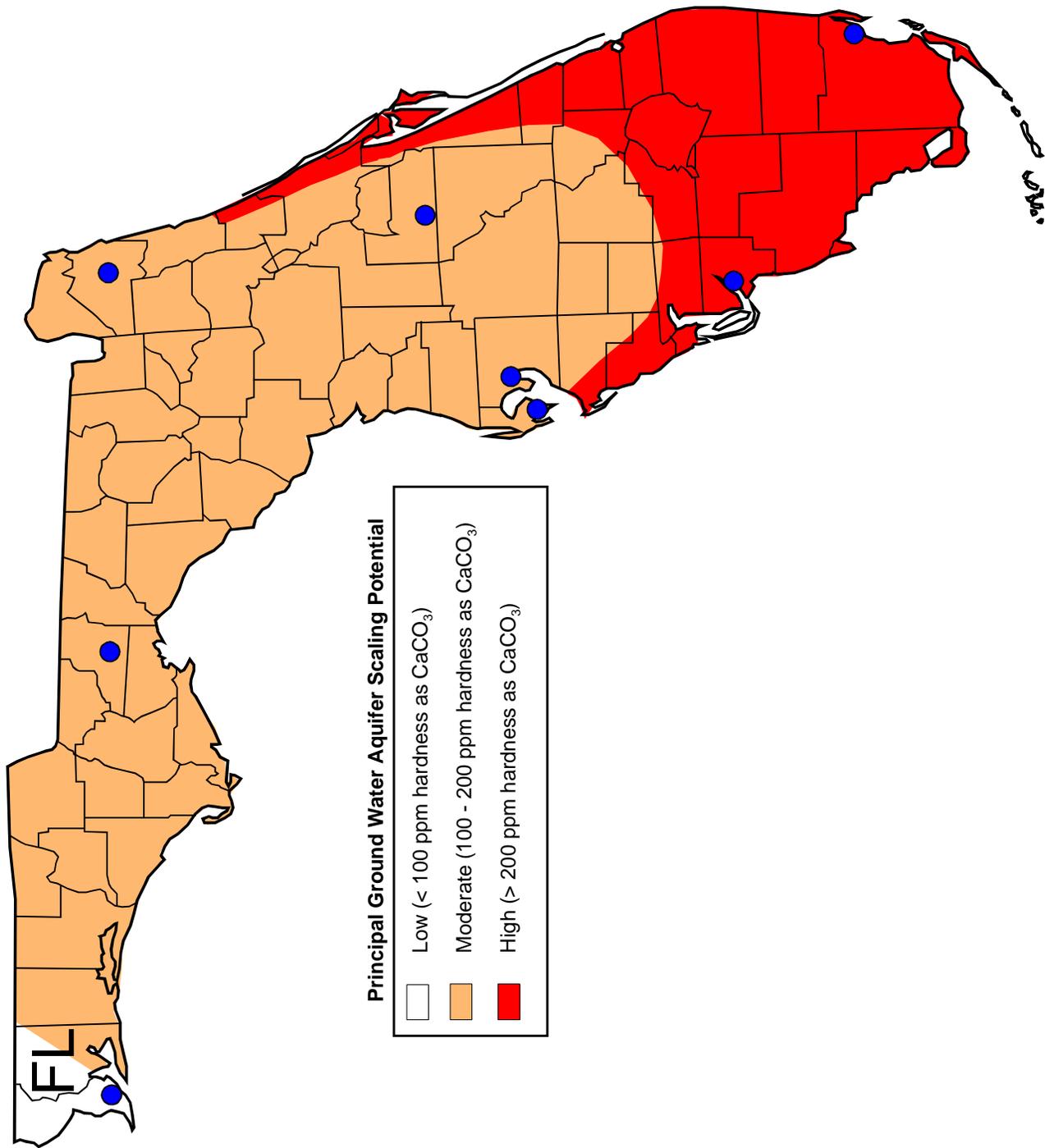


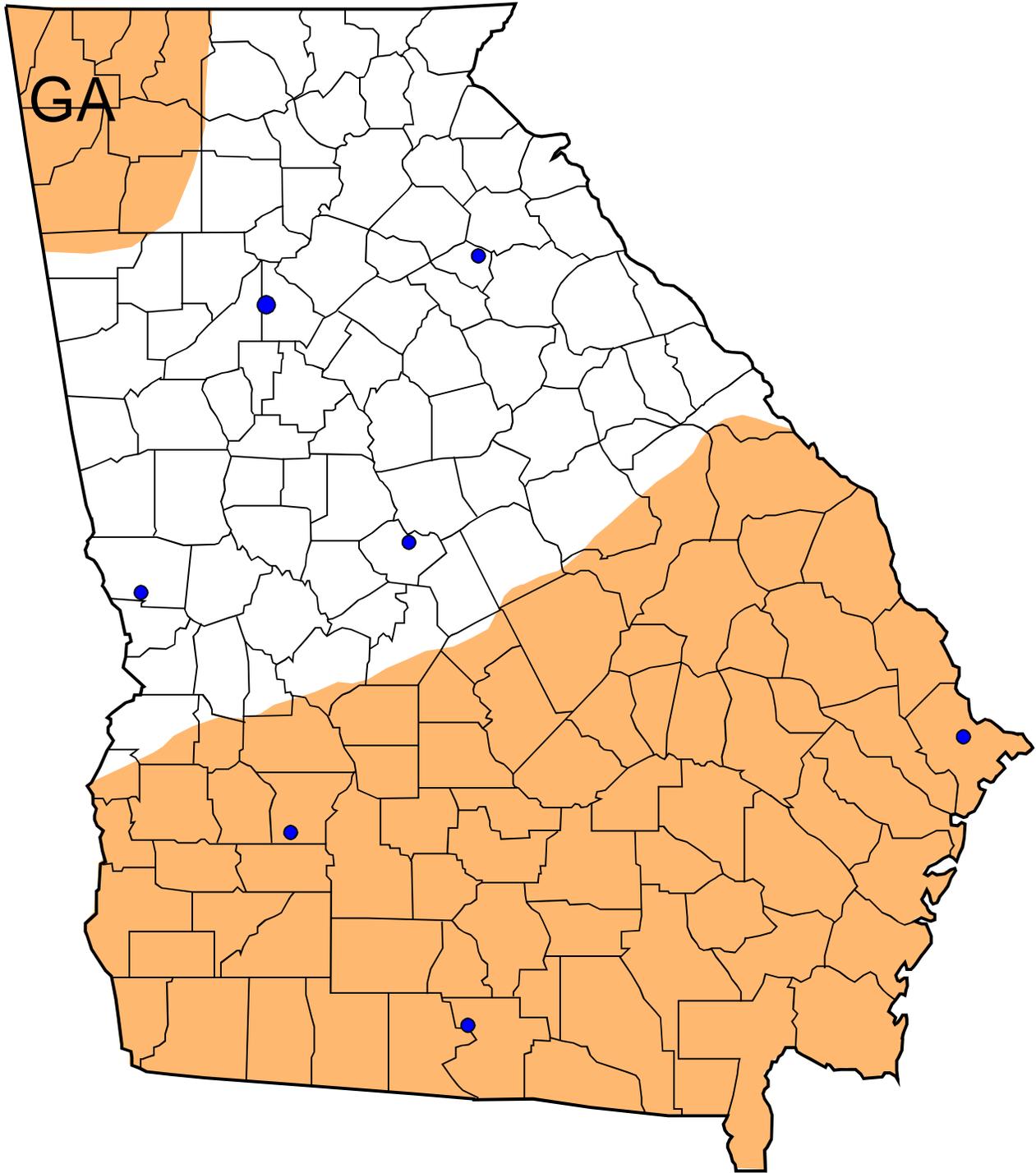
Principal Ground Water Aquifer Scaling Potential



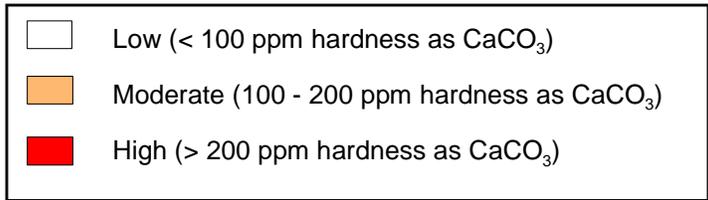


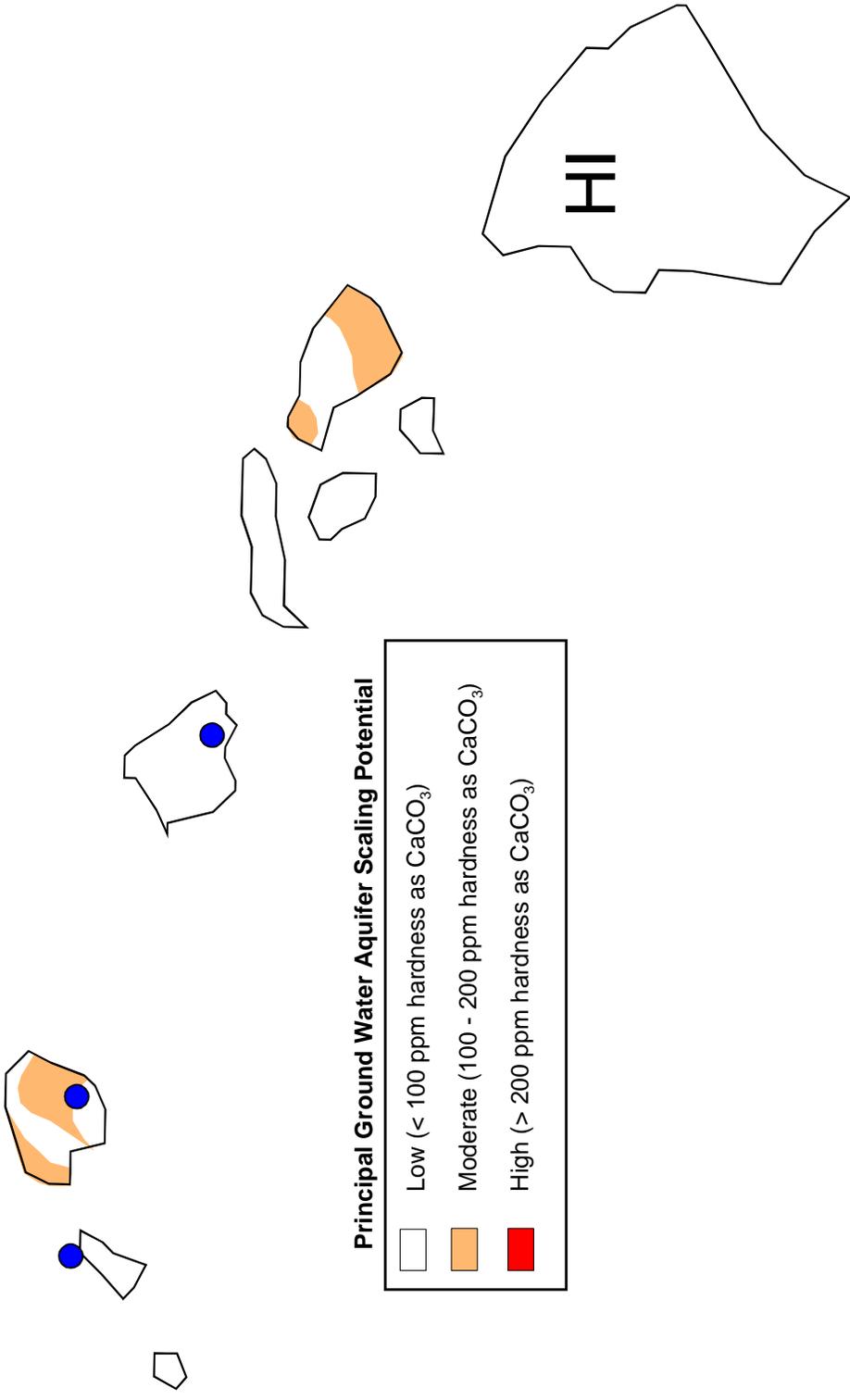






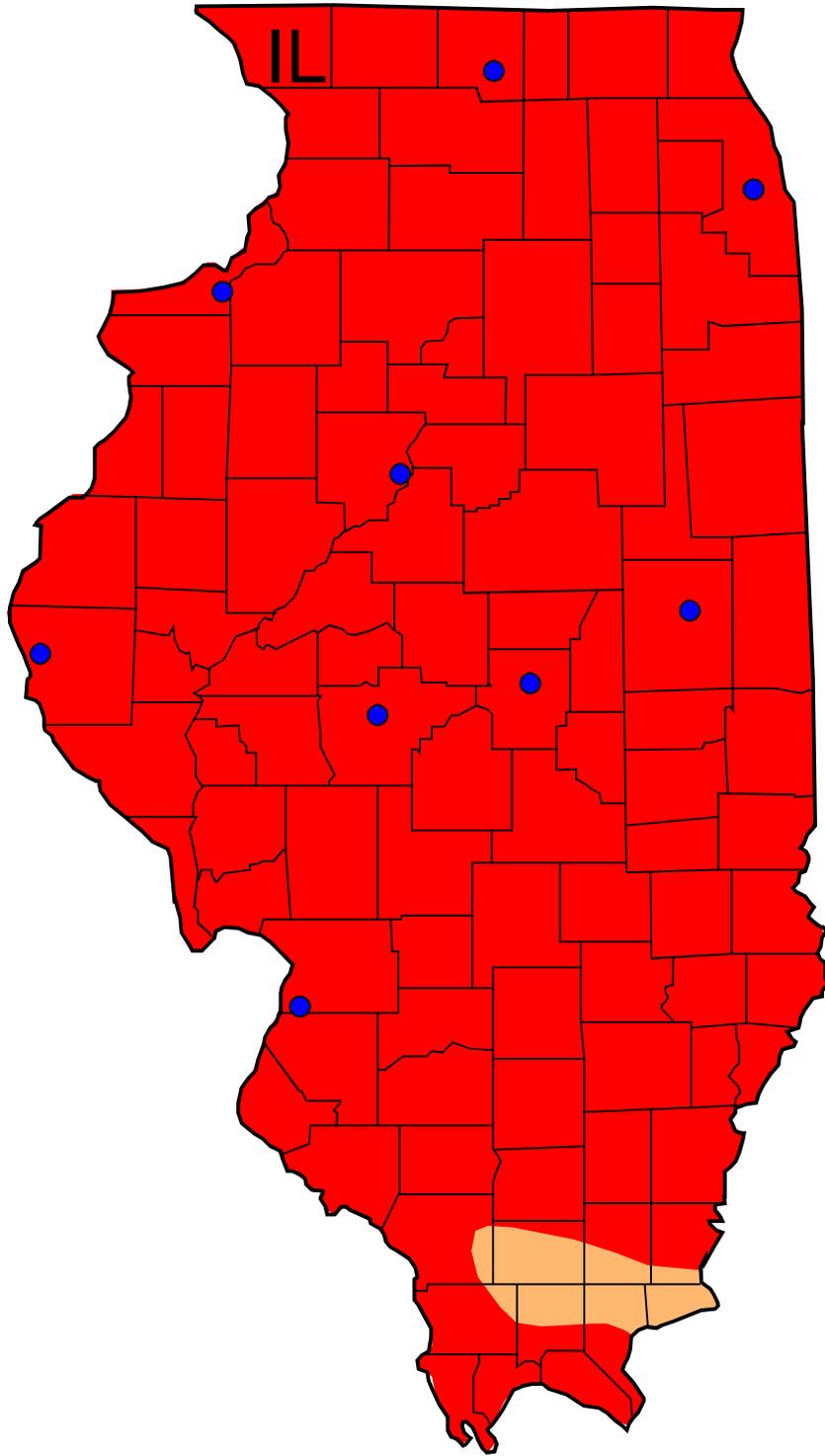
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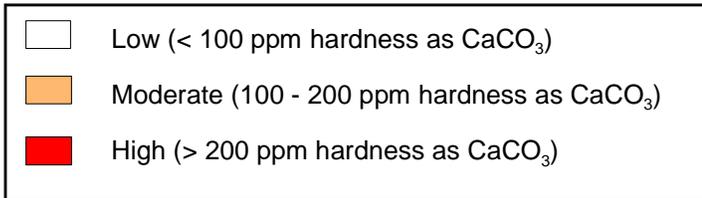


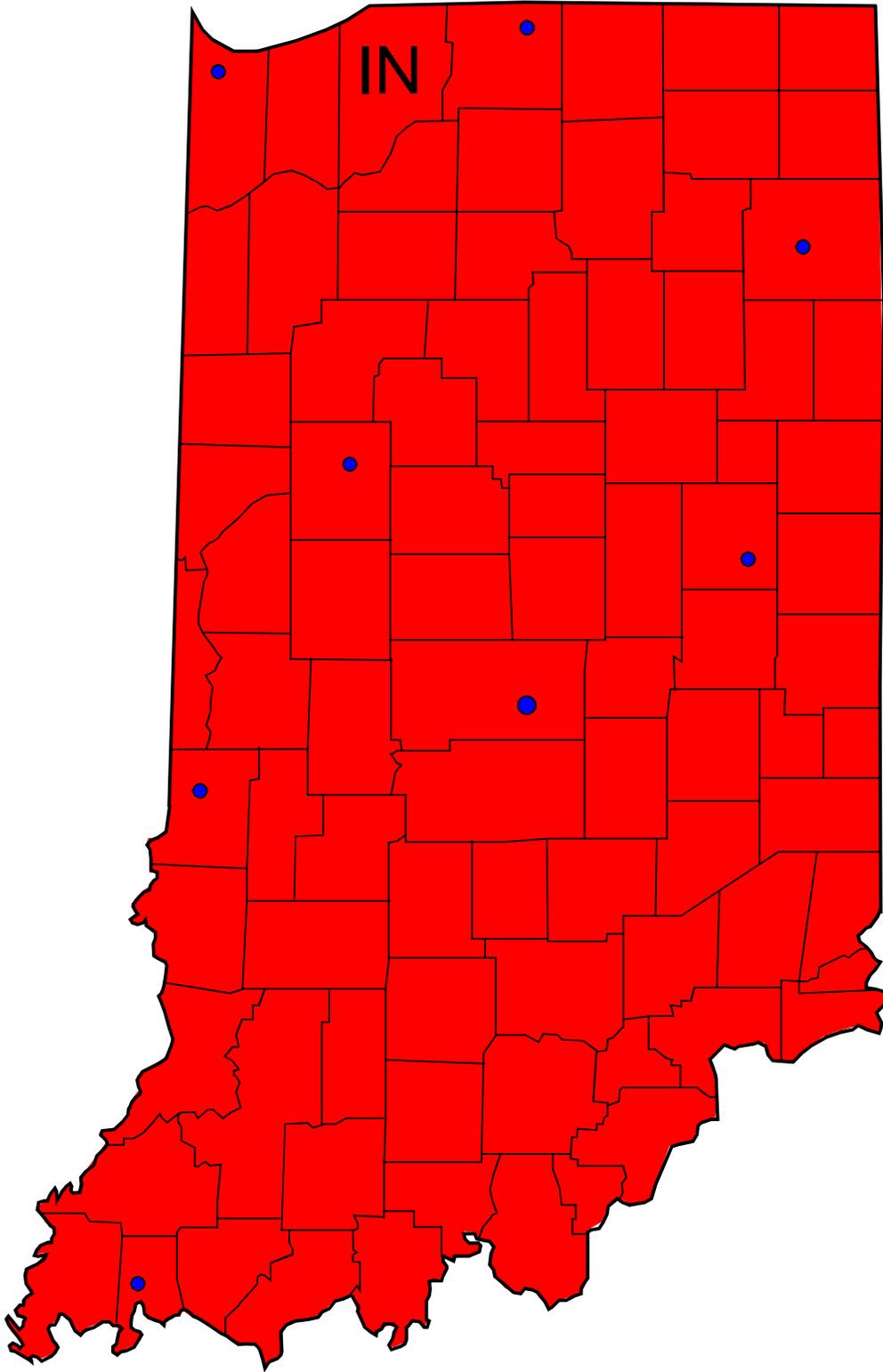
Principal Ground Water Aquifer Scaling Potential

- Low (< 100 ppm hardness as CaCO₃)
- Moderate (100 - 200 ppm hardness as CaCO₃)
- High (> 200 ppm hardness as CaCO₃)

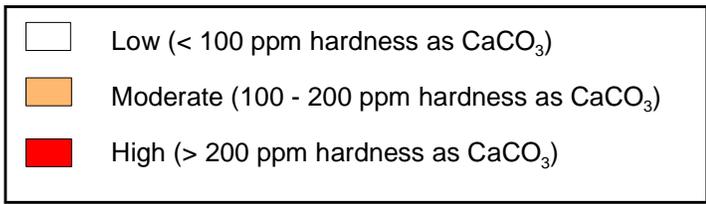


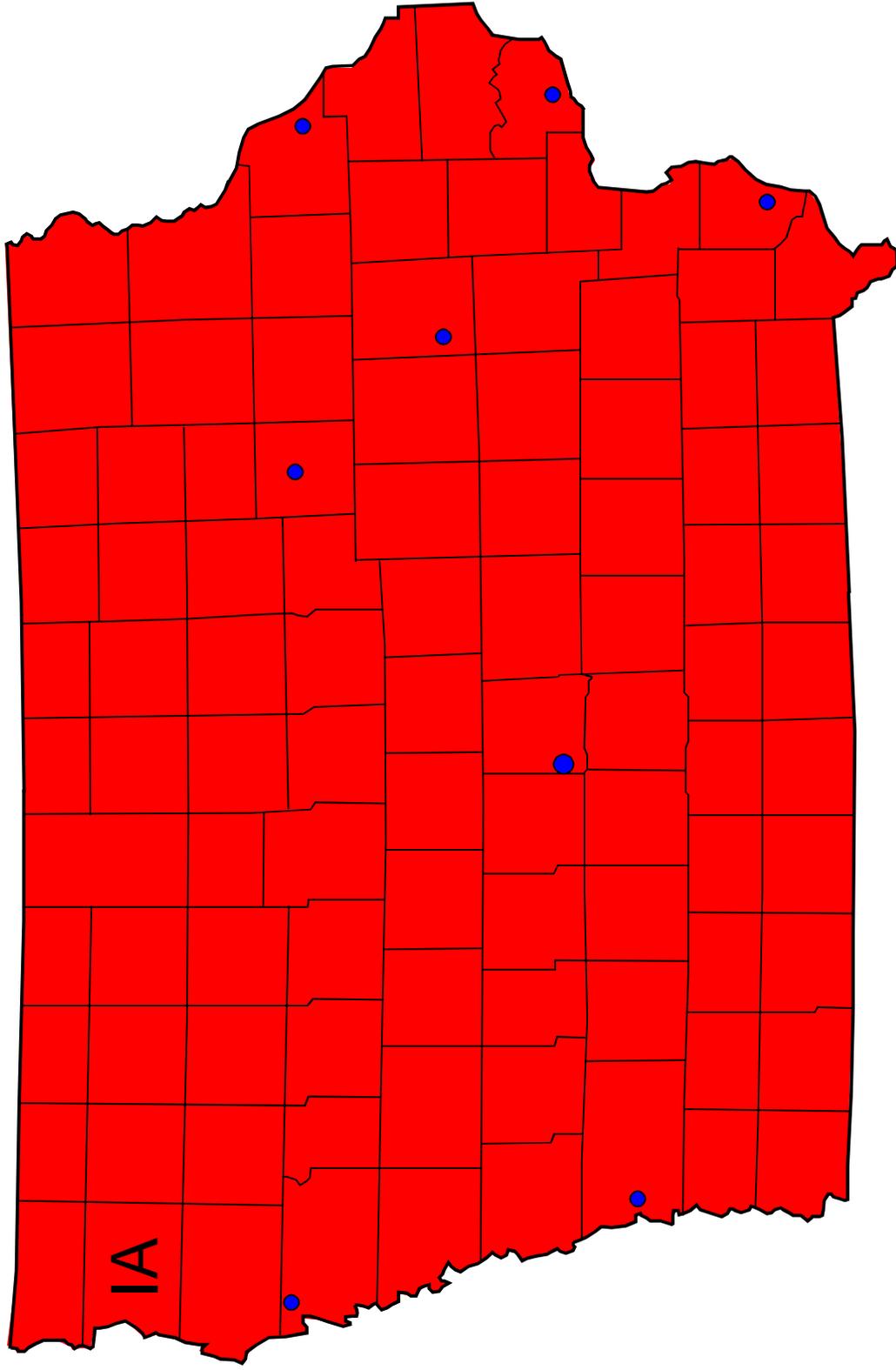
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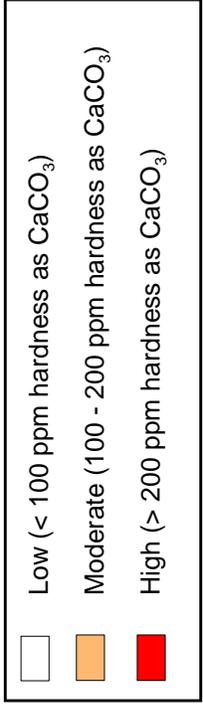


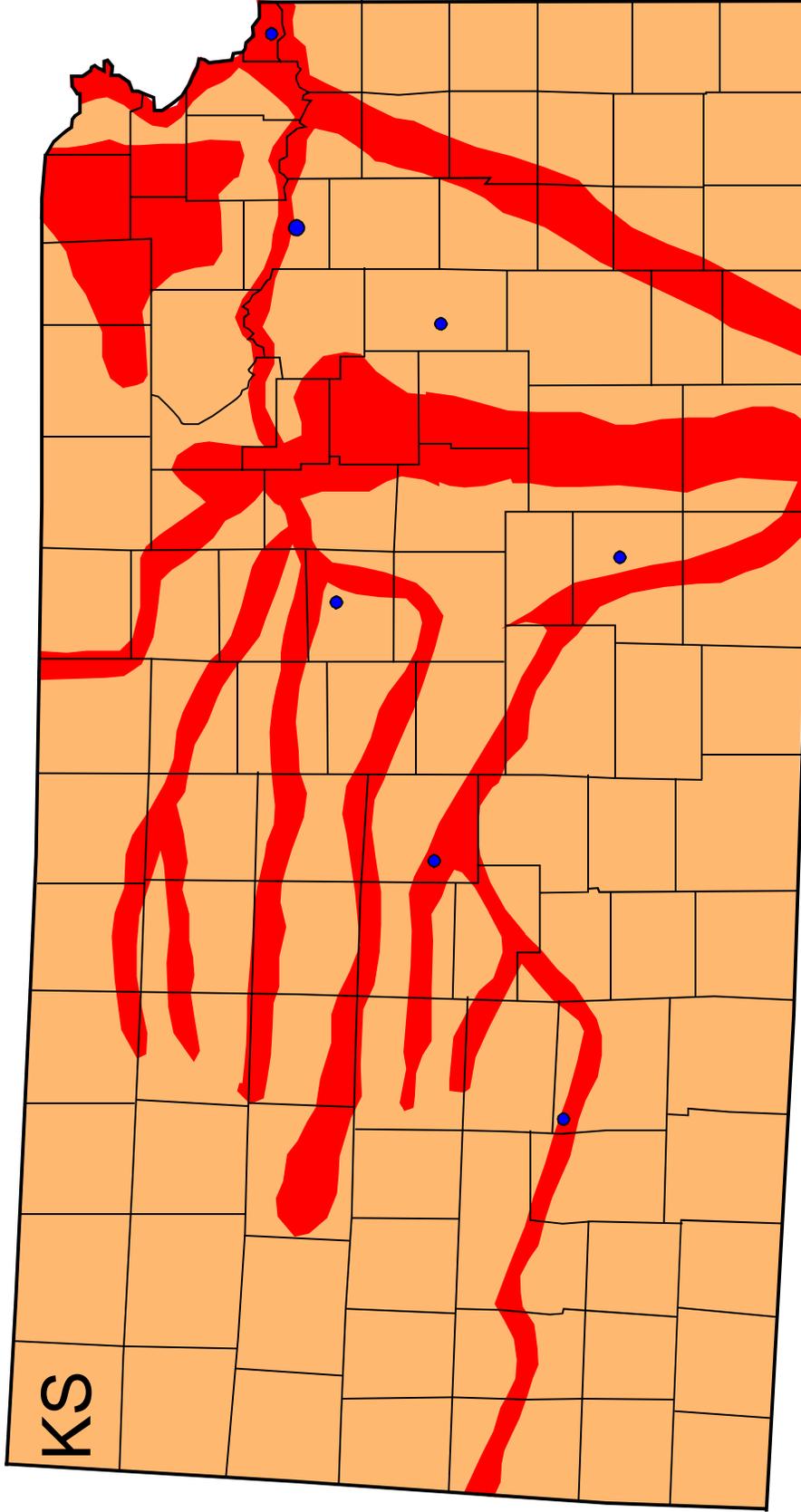
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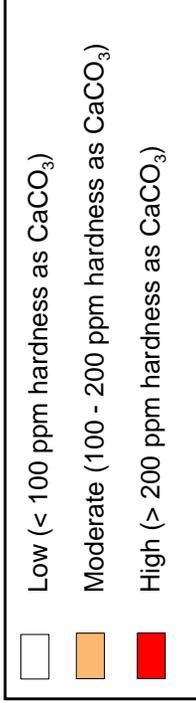
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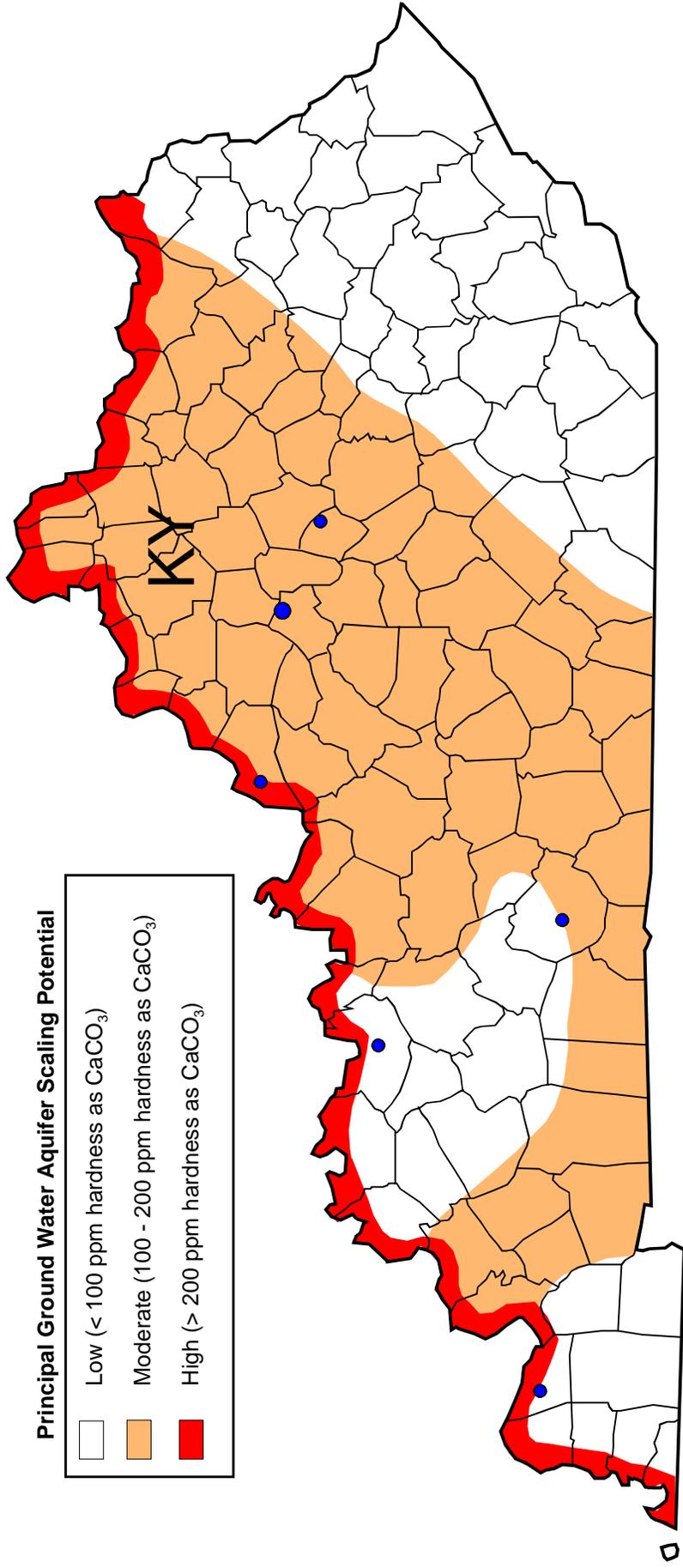
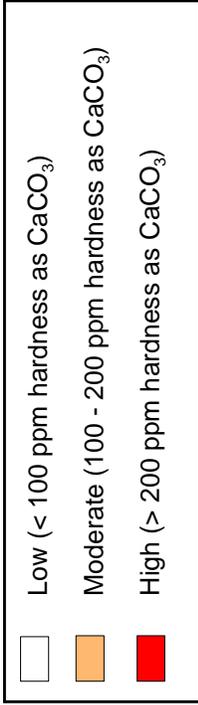


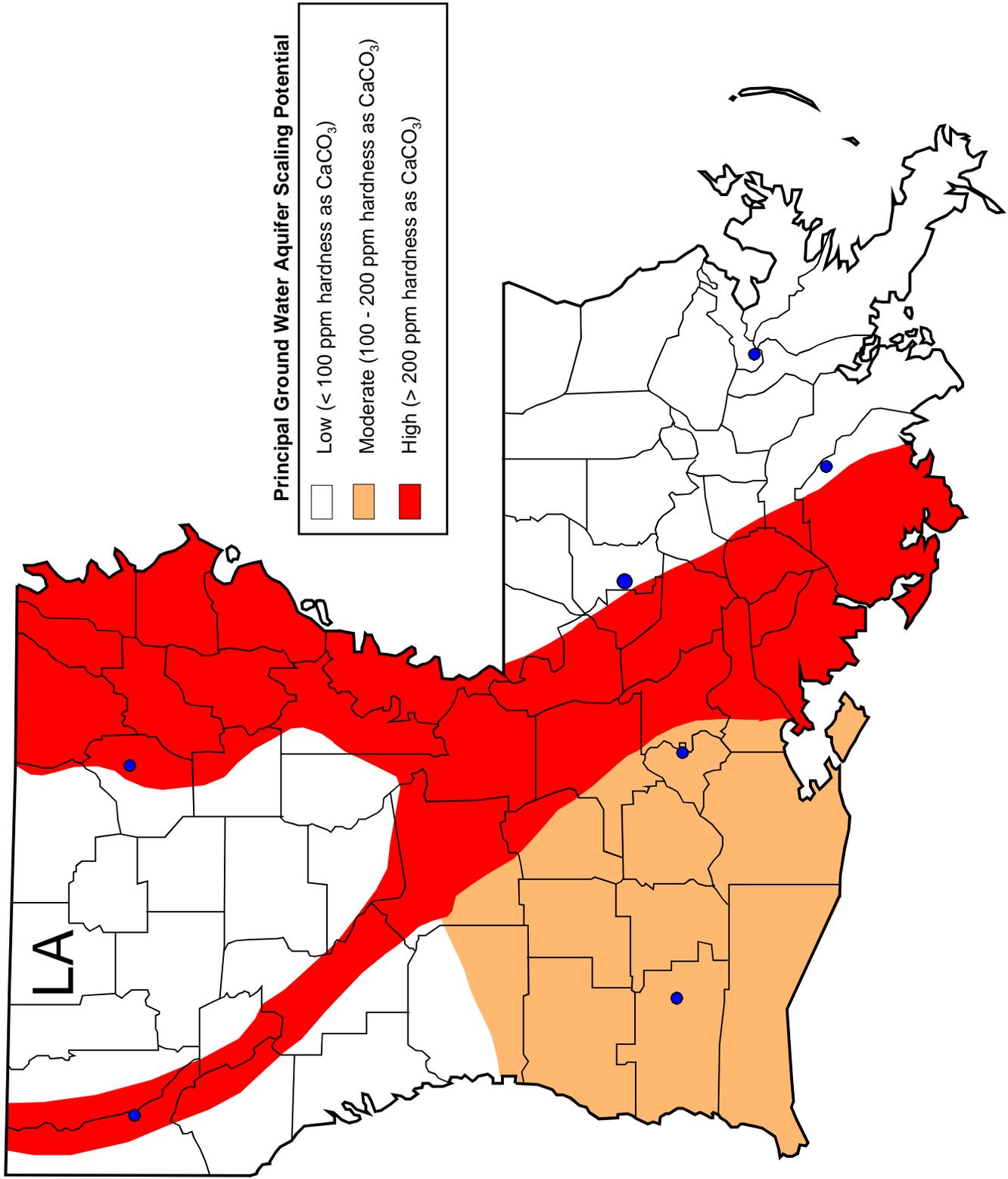
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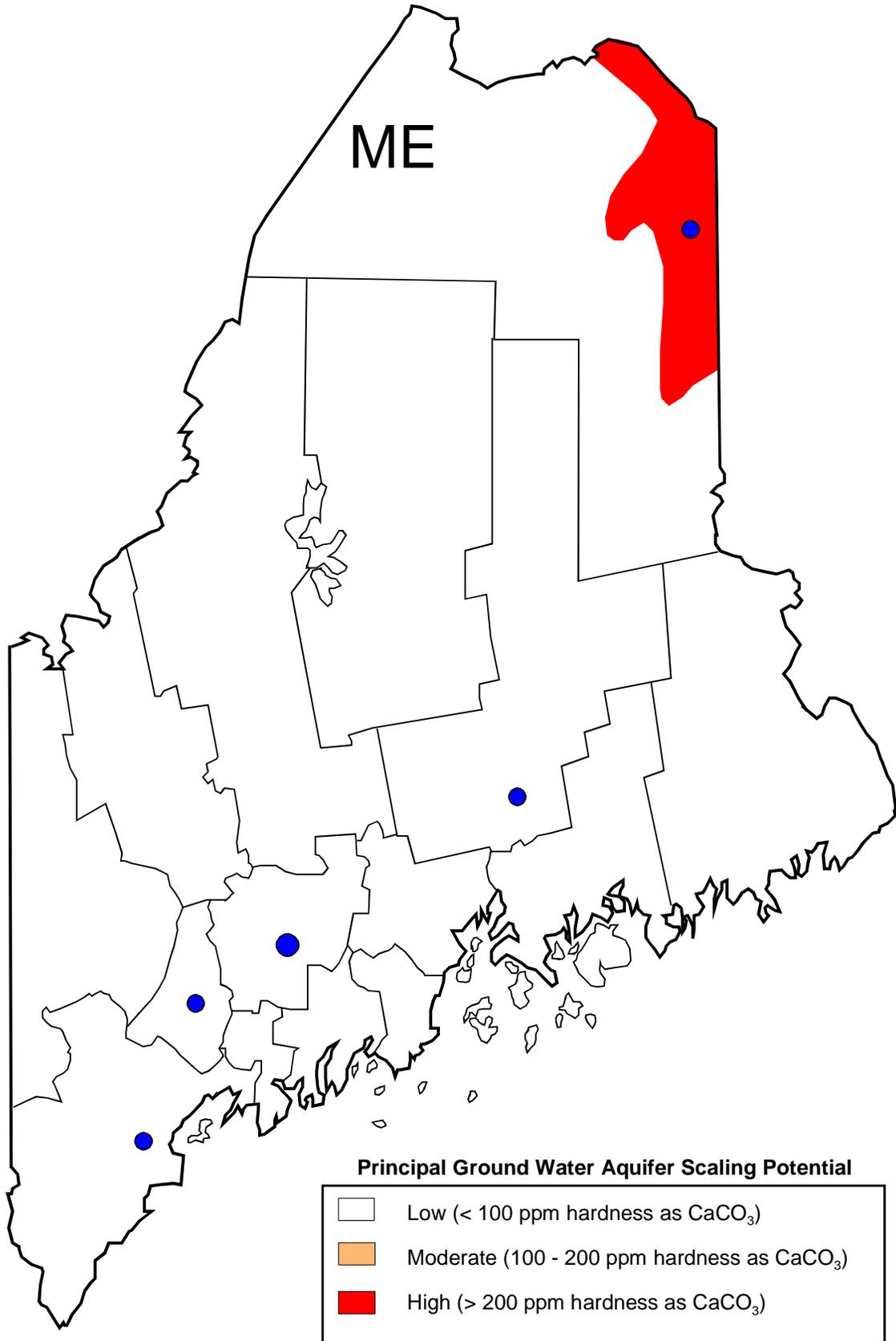
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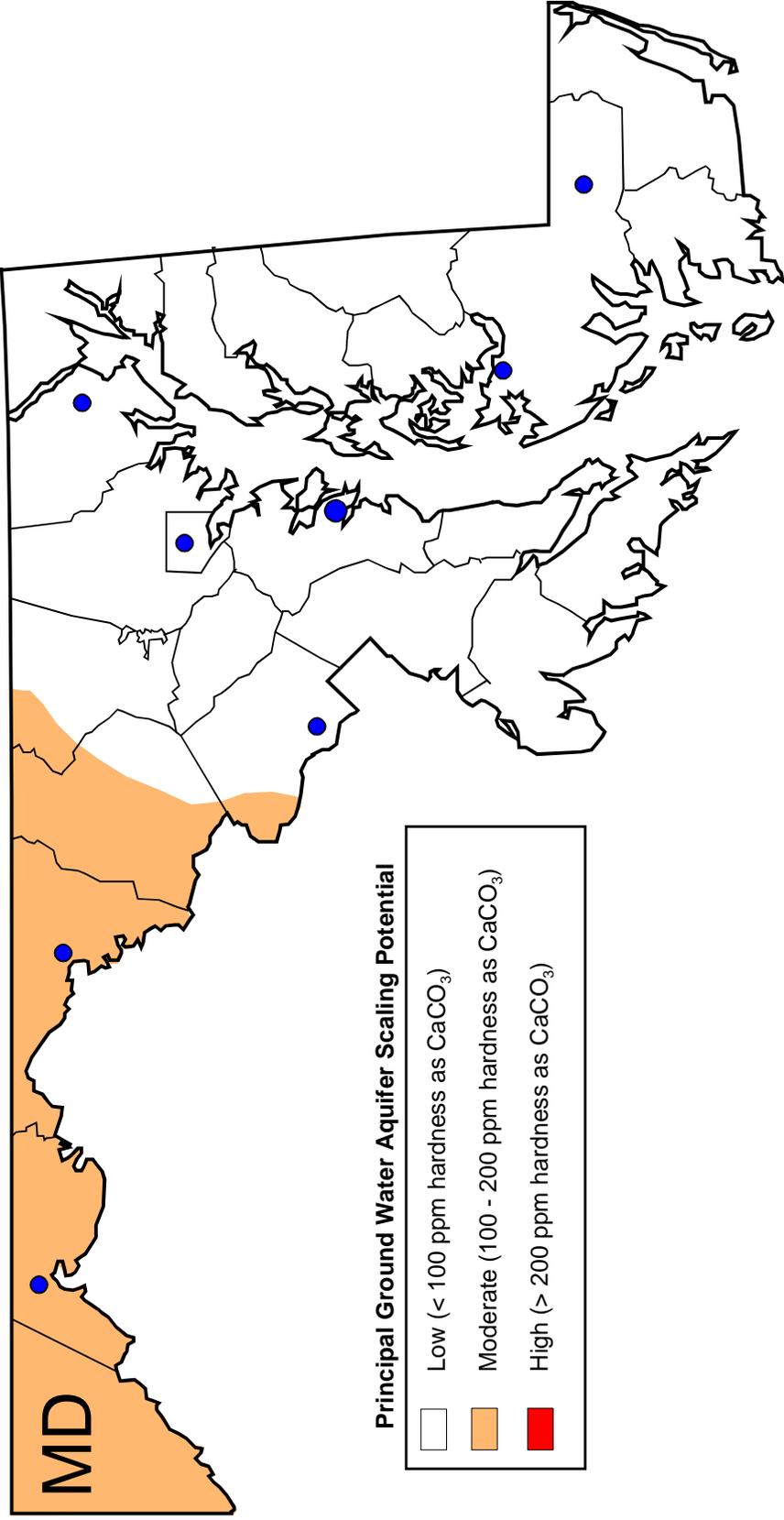


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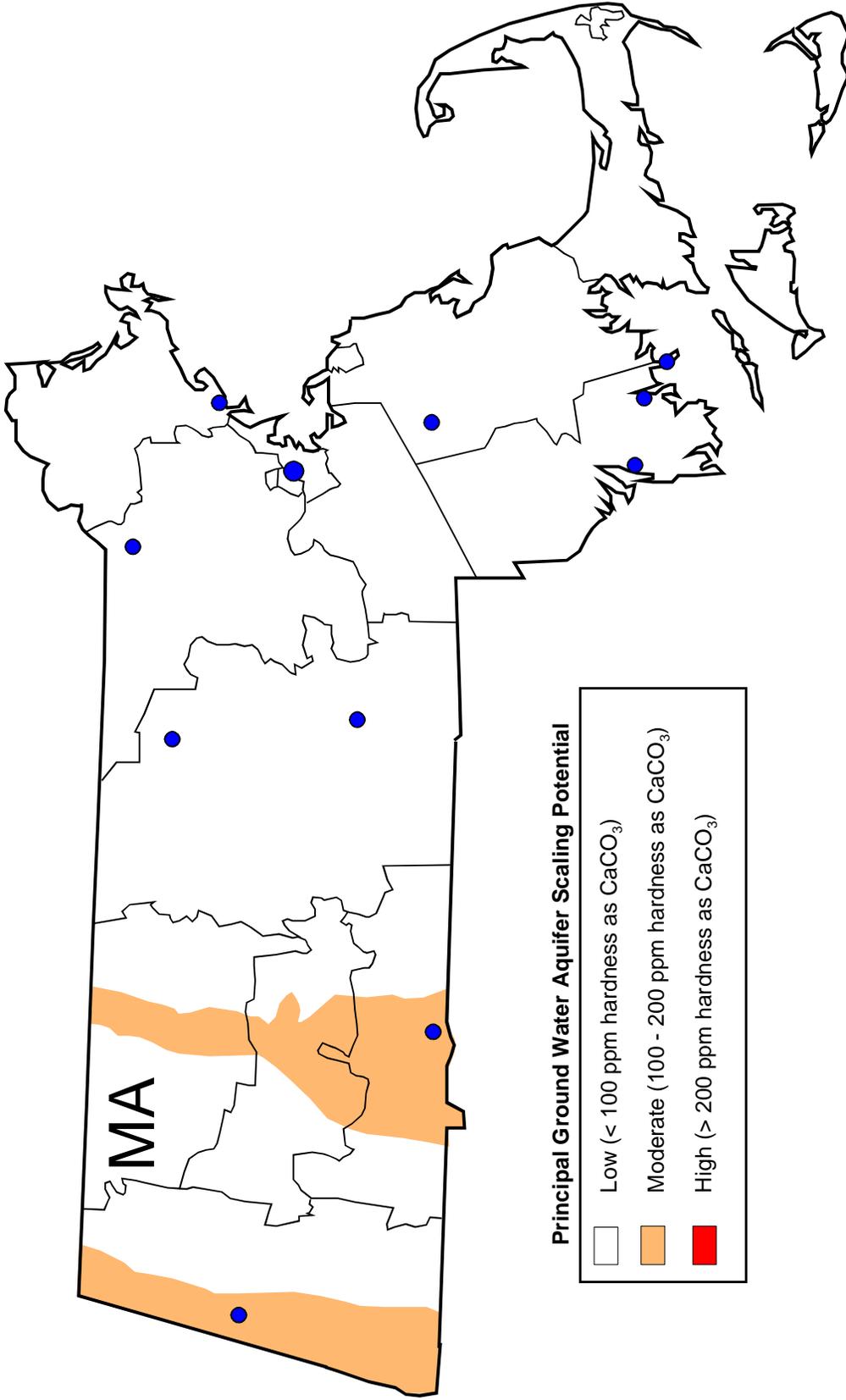




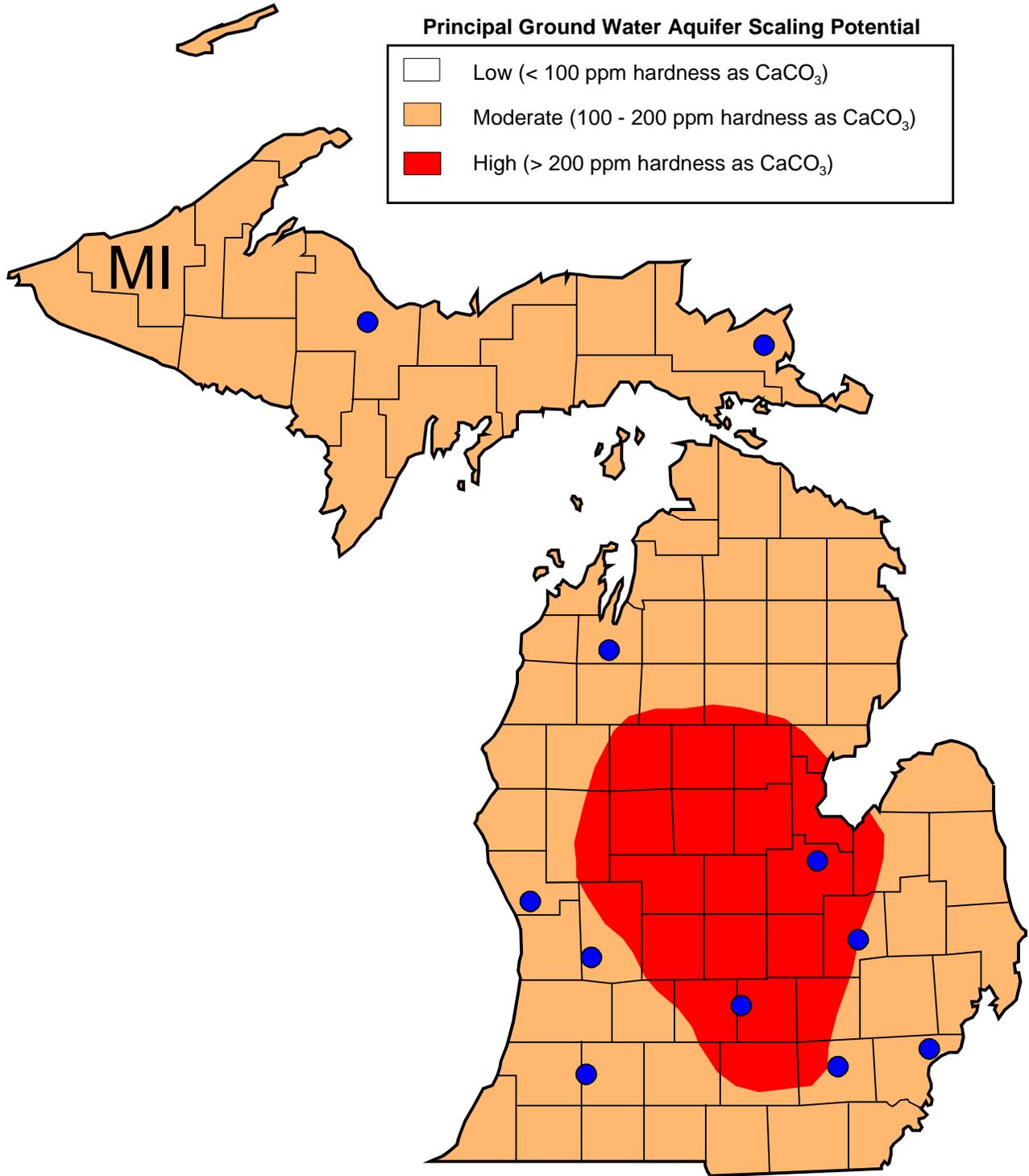
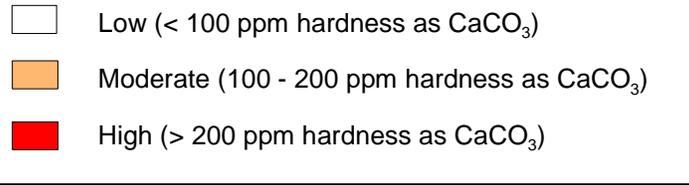


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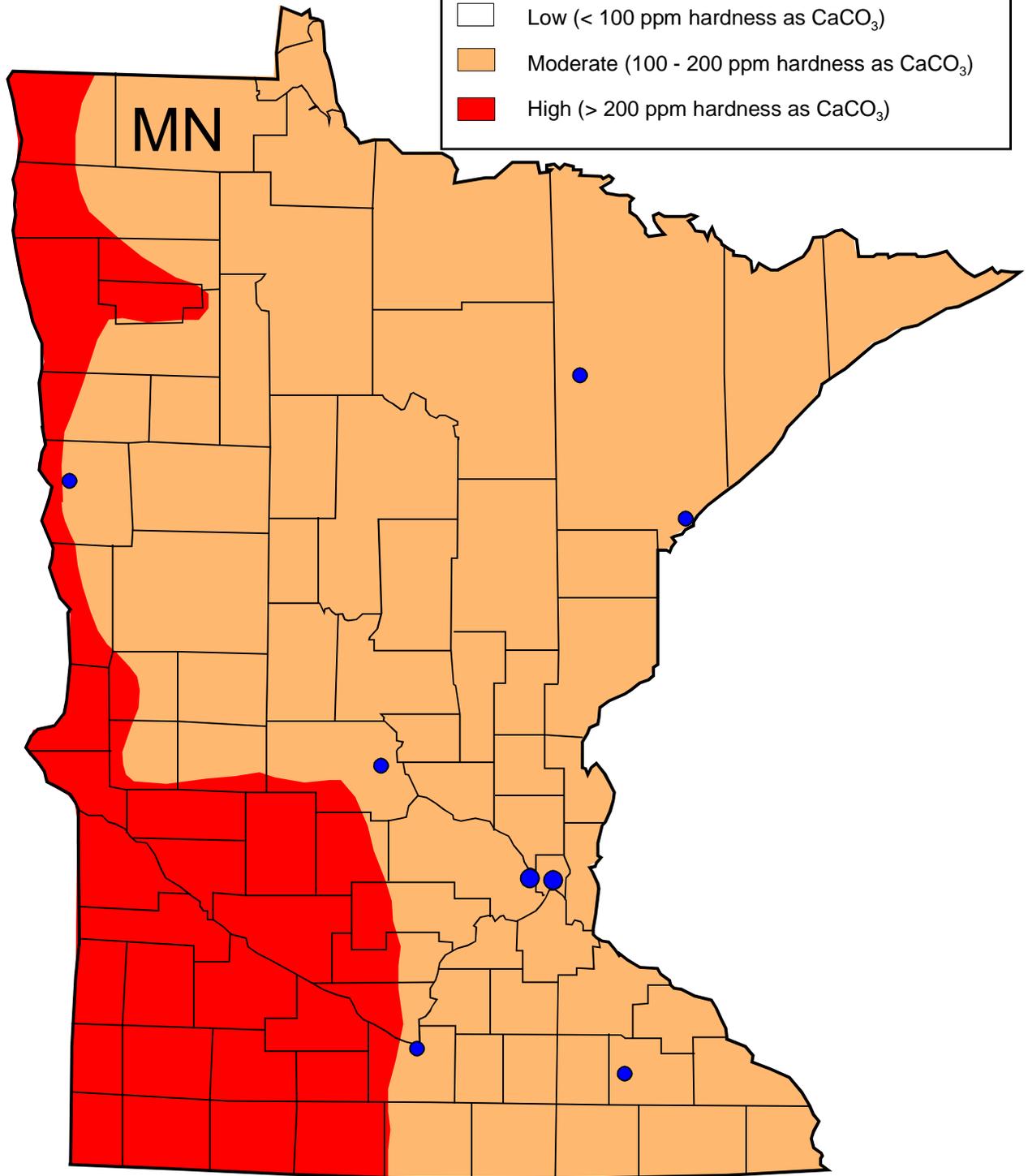
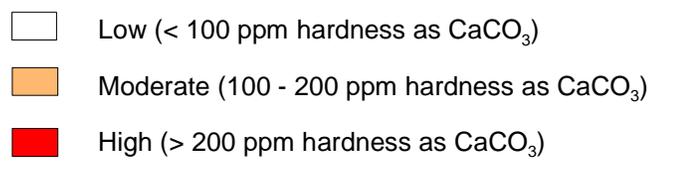
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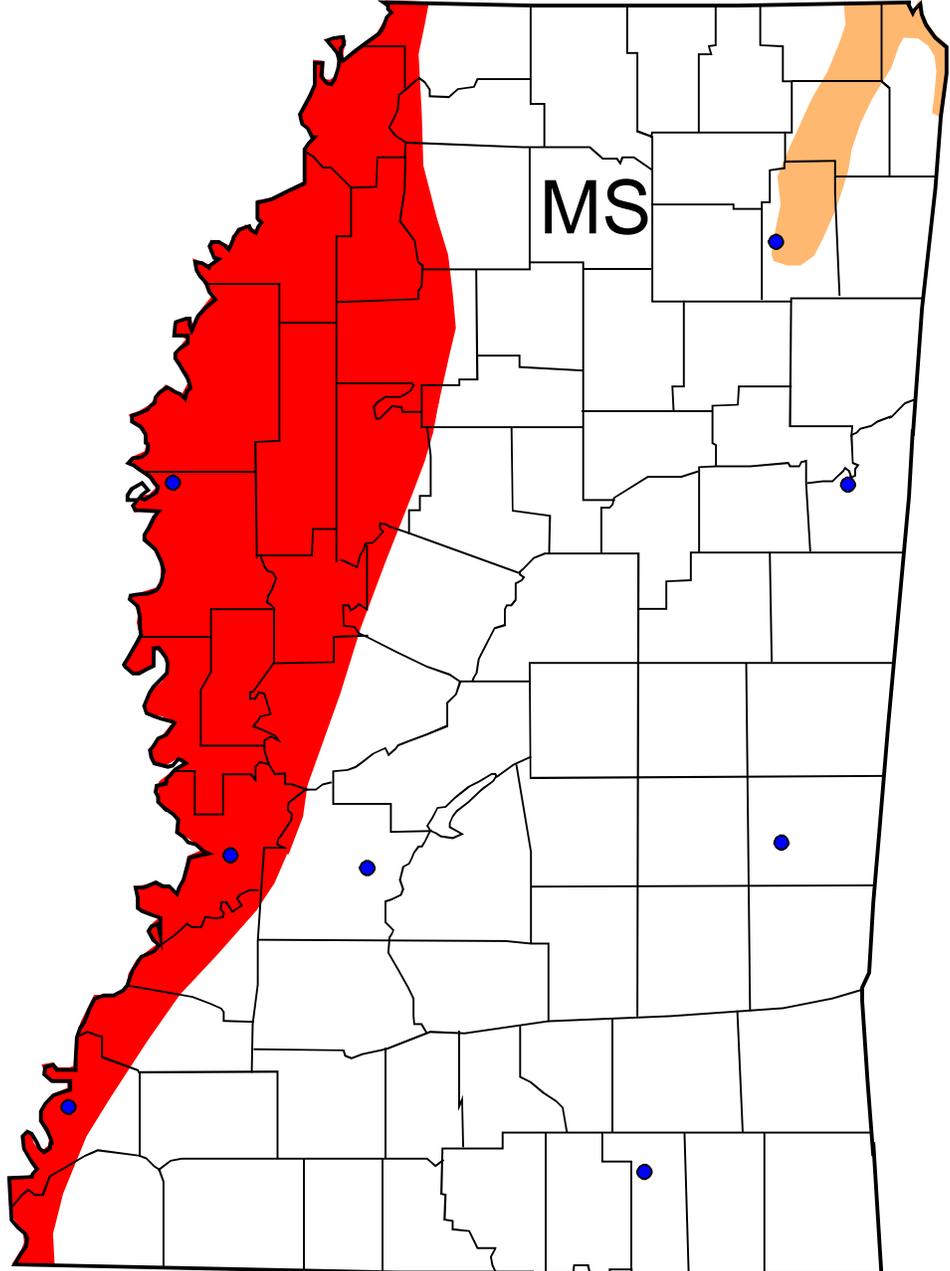


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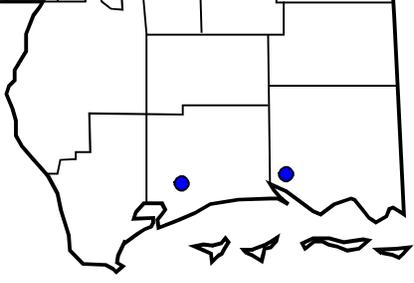
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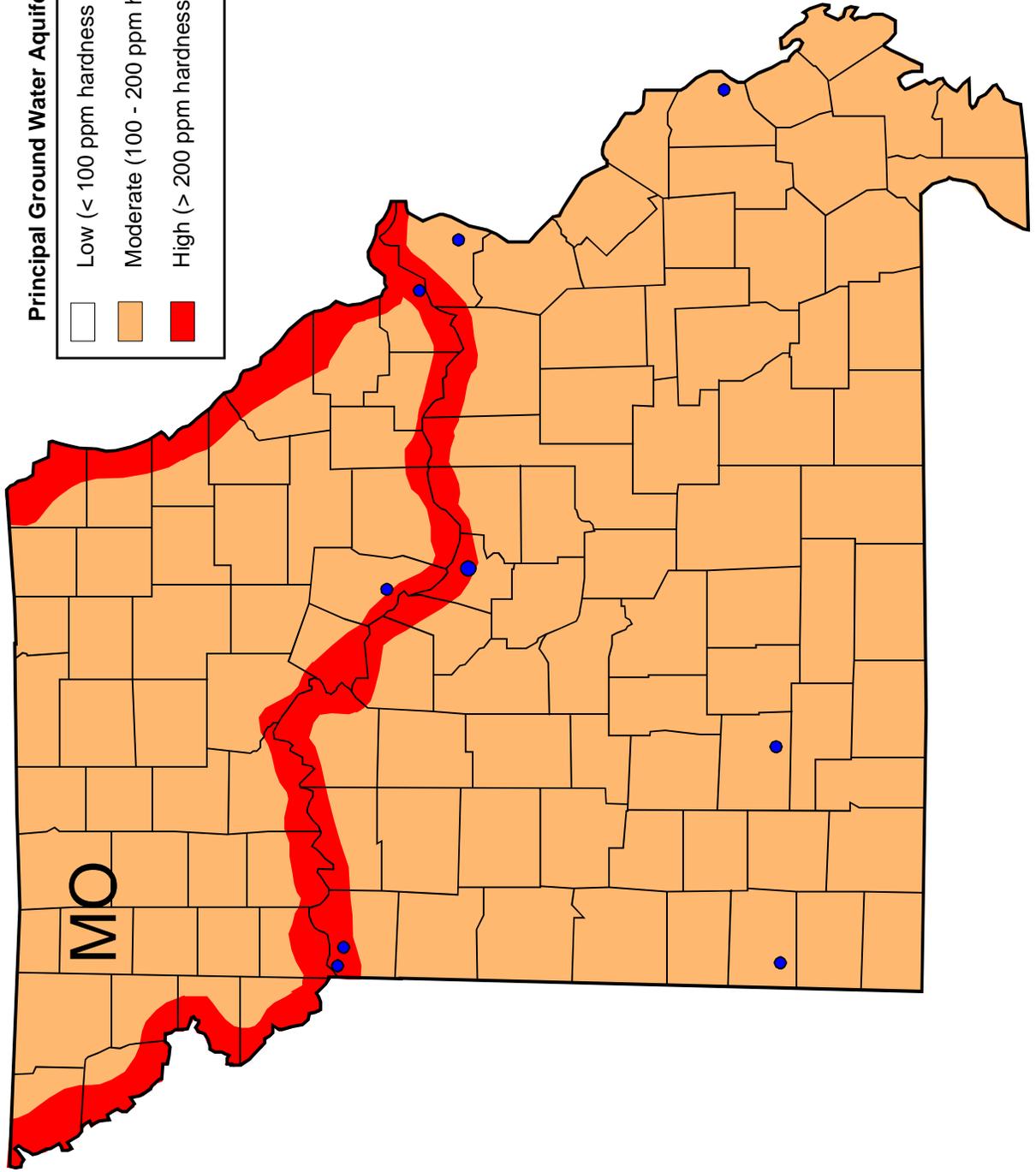
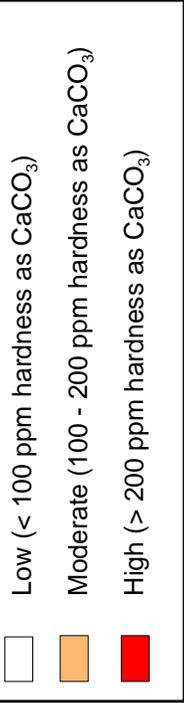


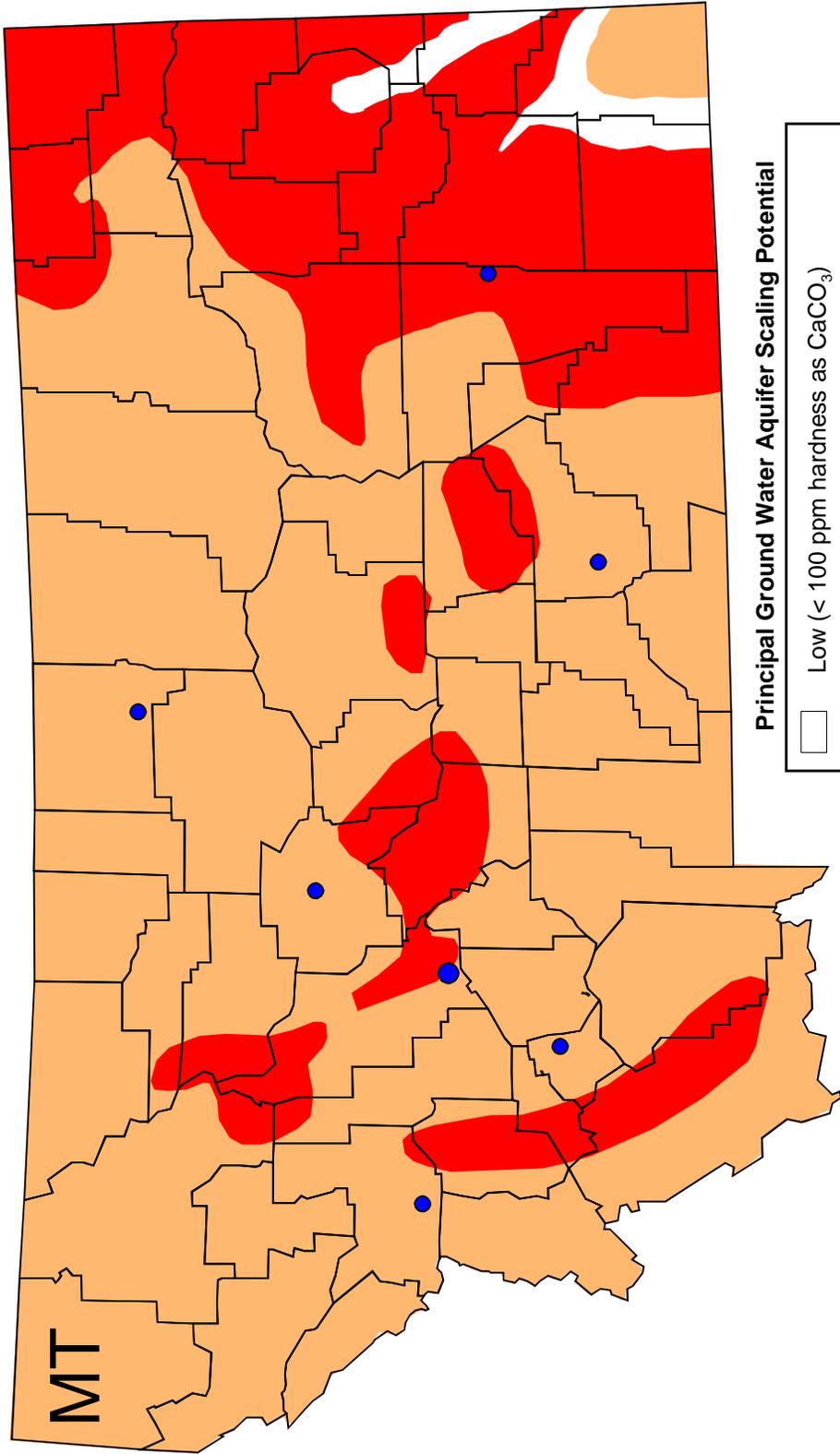
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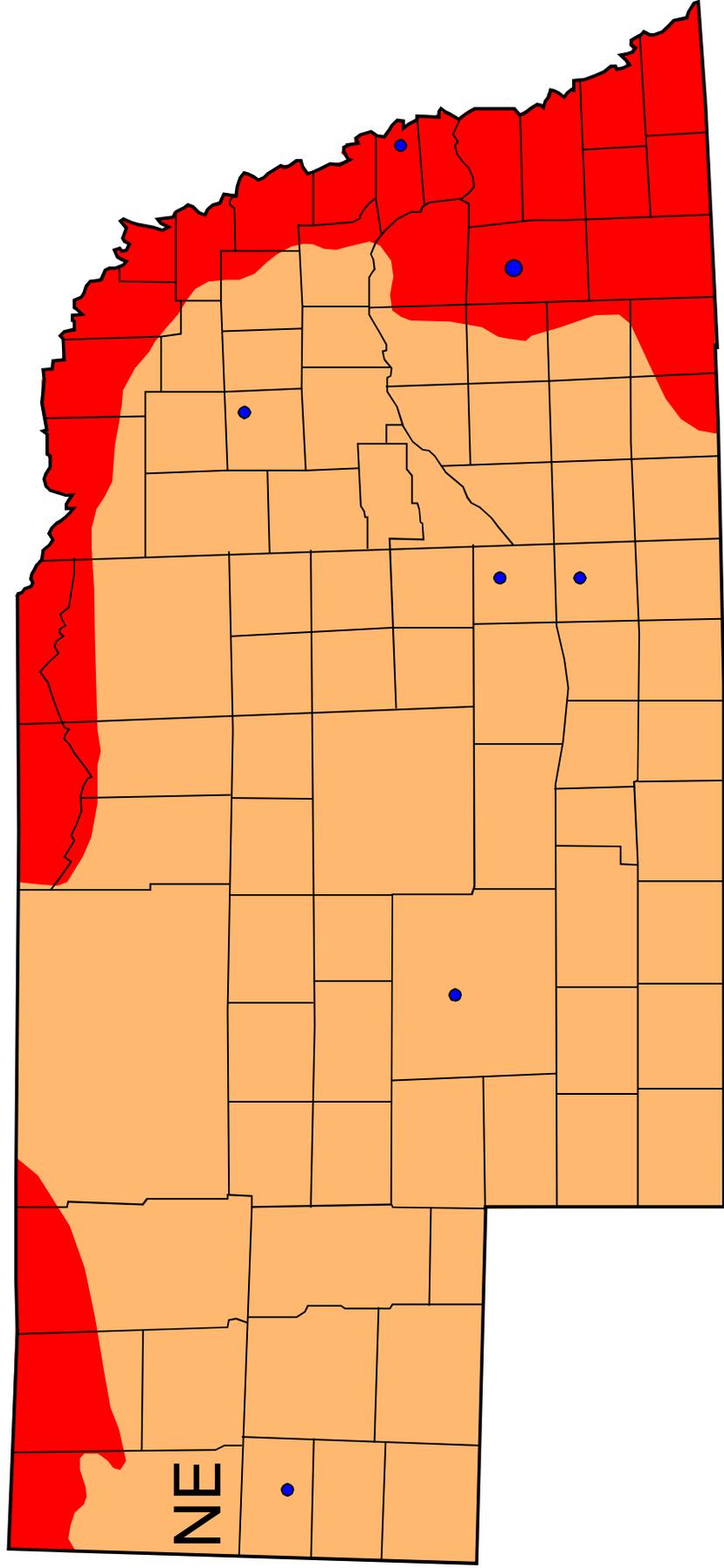
Principal Ground Water Aquifer Scaling Potential



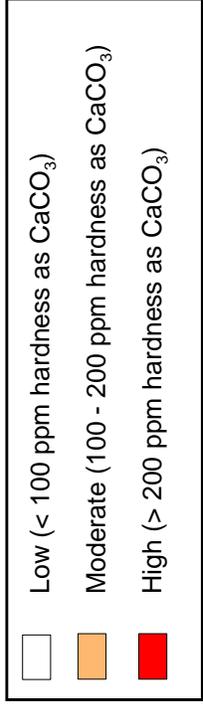


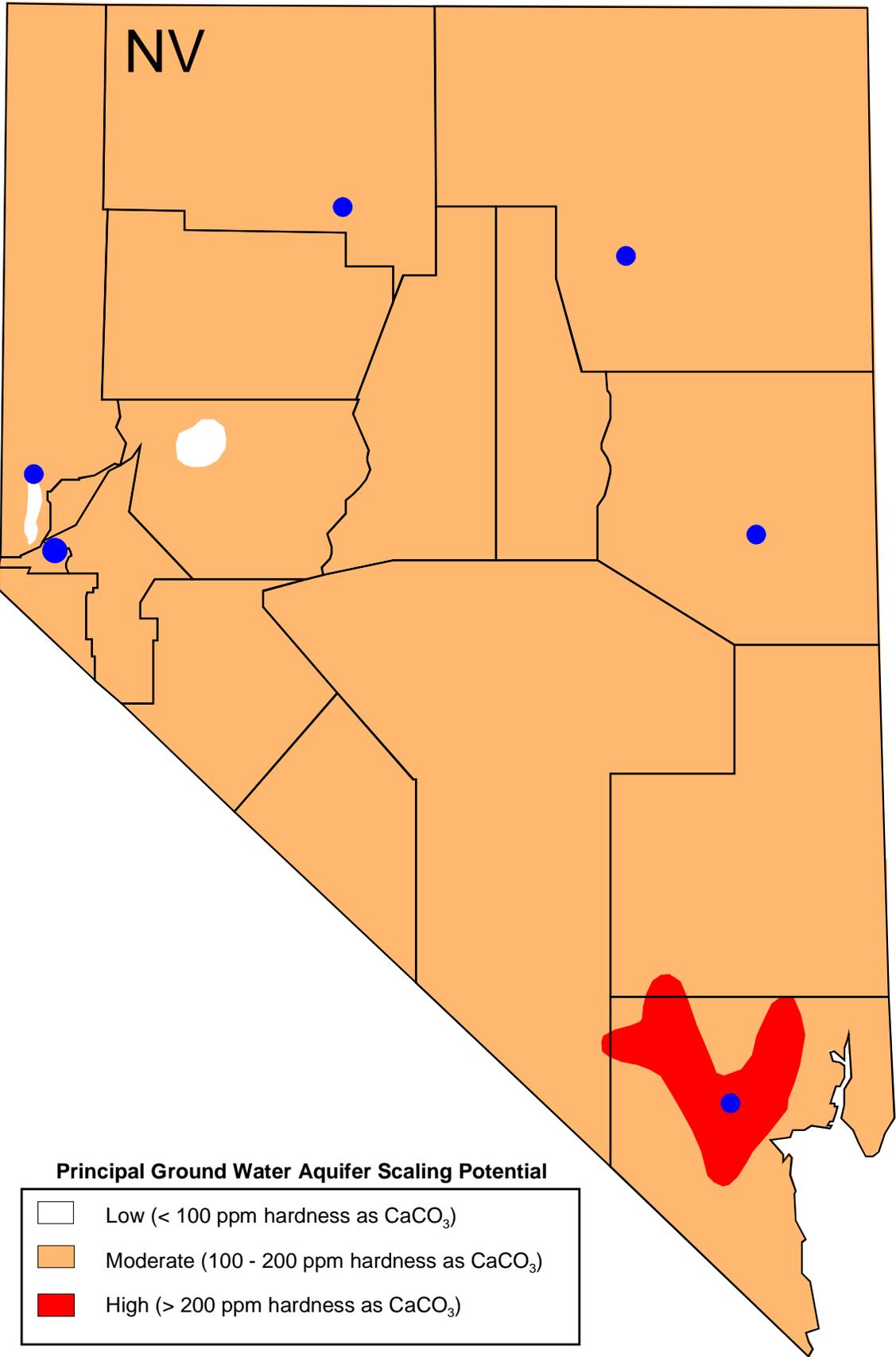
Principal Ground Water Aquifer Scaling Potential





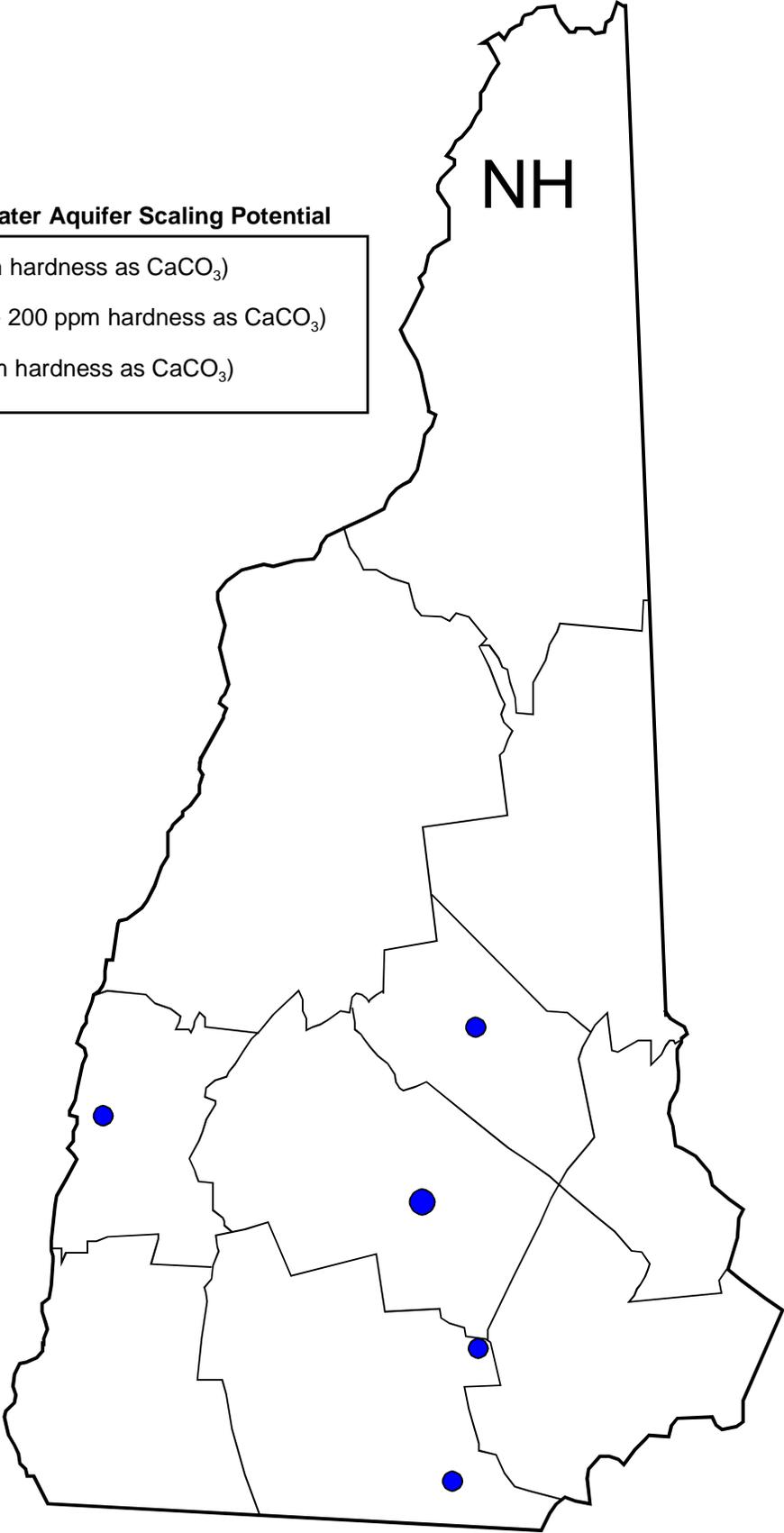
Principal Ground Water Aquifer Scaling Potential

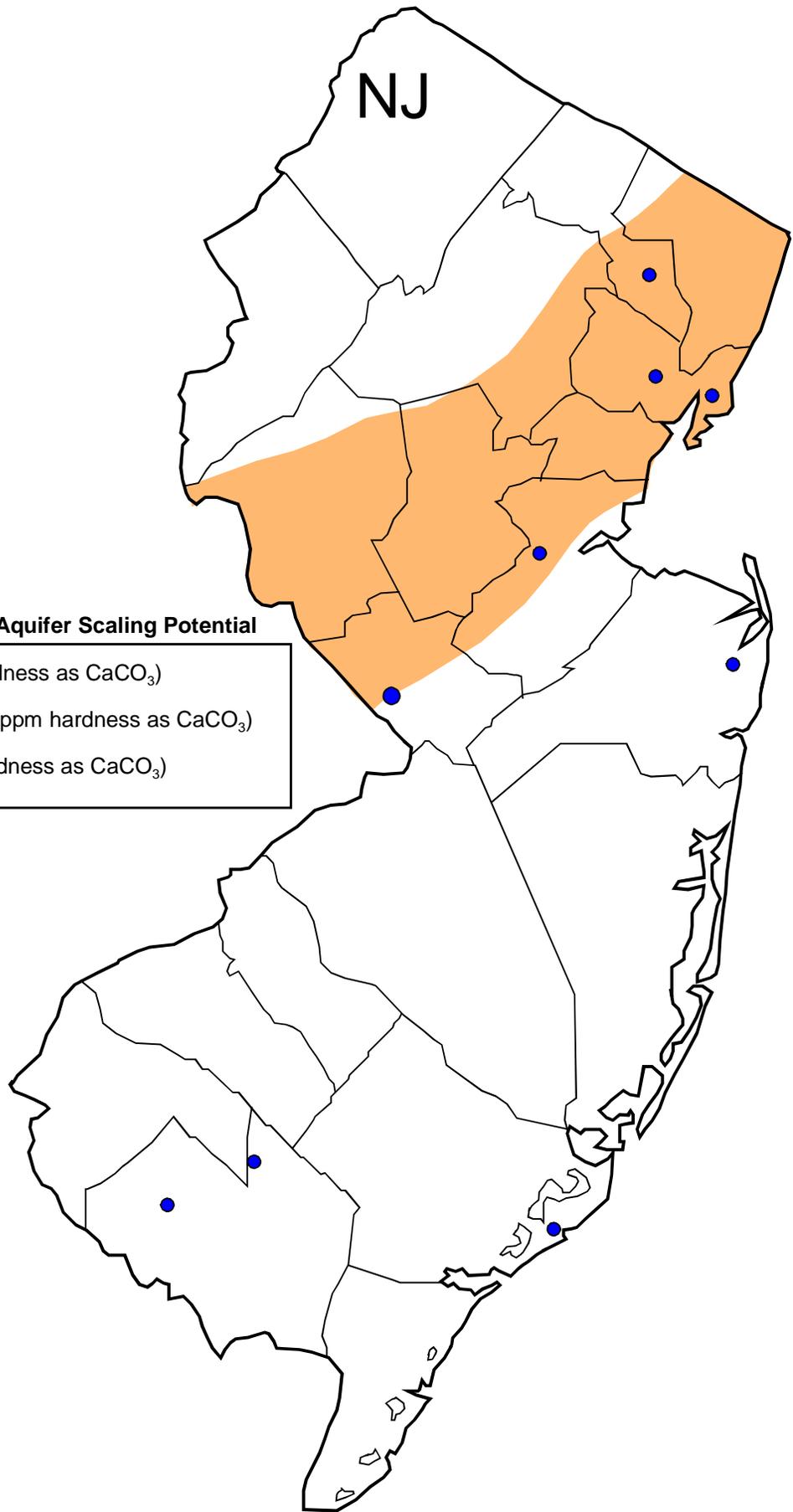




Principal Ground Water Aquifer Scaling Potential

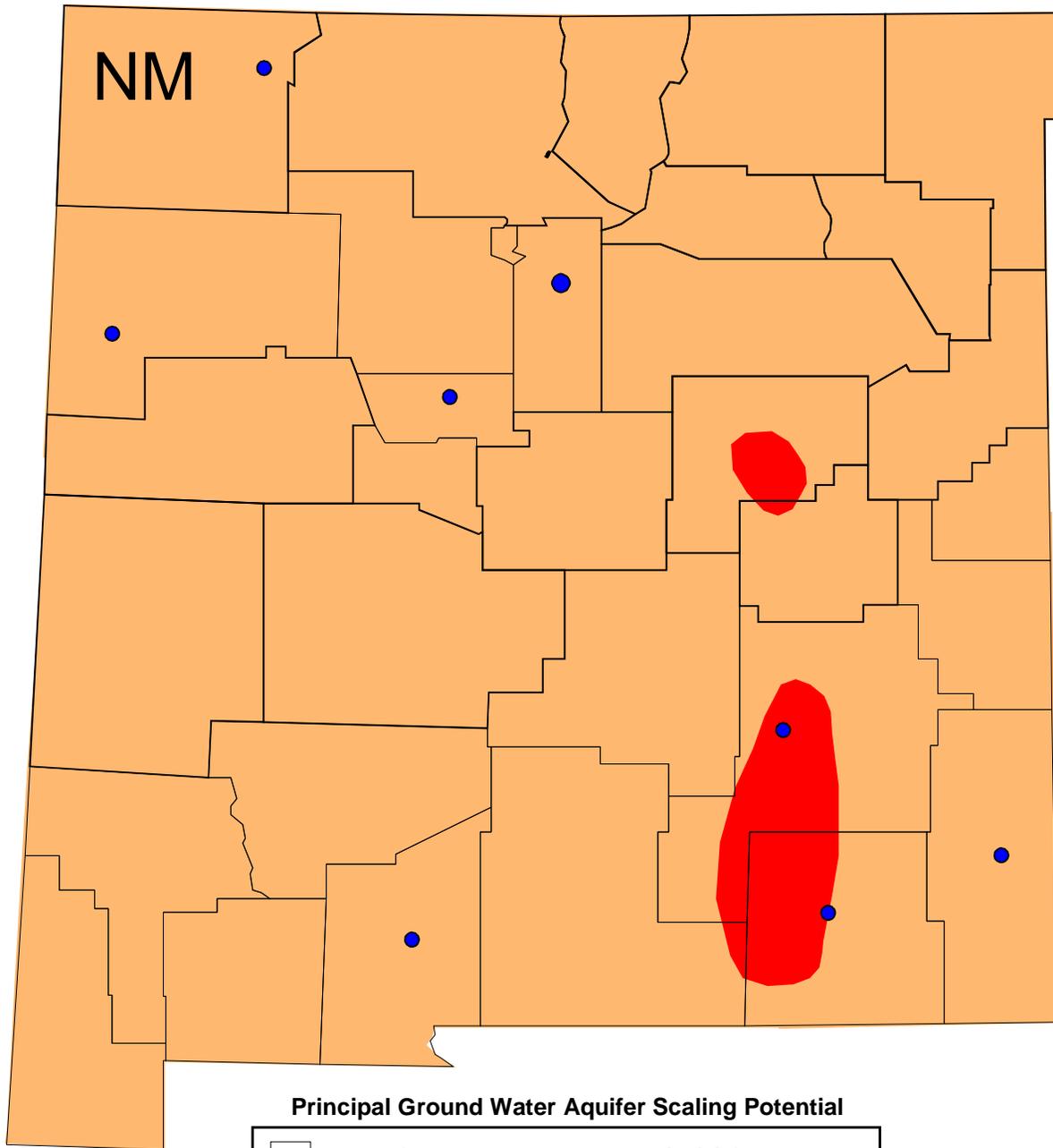
	Low (< 100 ppm hardness as CaCO ₃)
	Moderate (100 - 200 ppm hardness as CaCO ₃)
	High (> 200 ppm hardness as CaCO ₃)

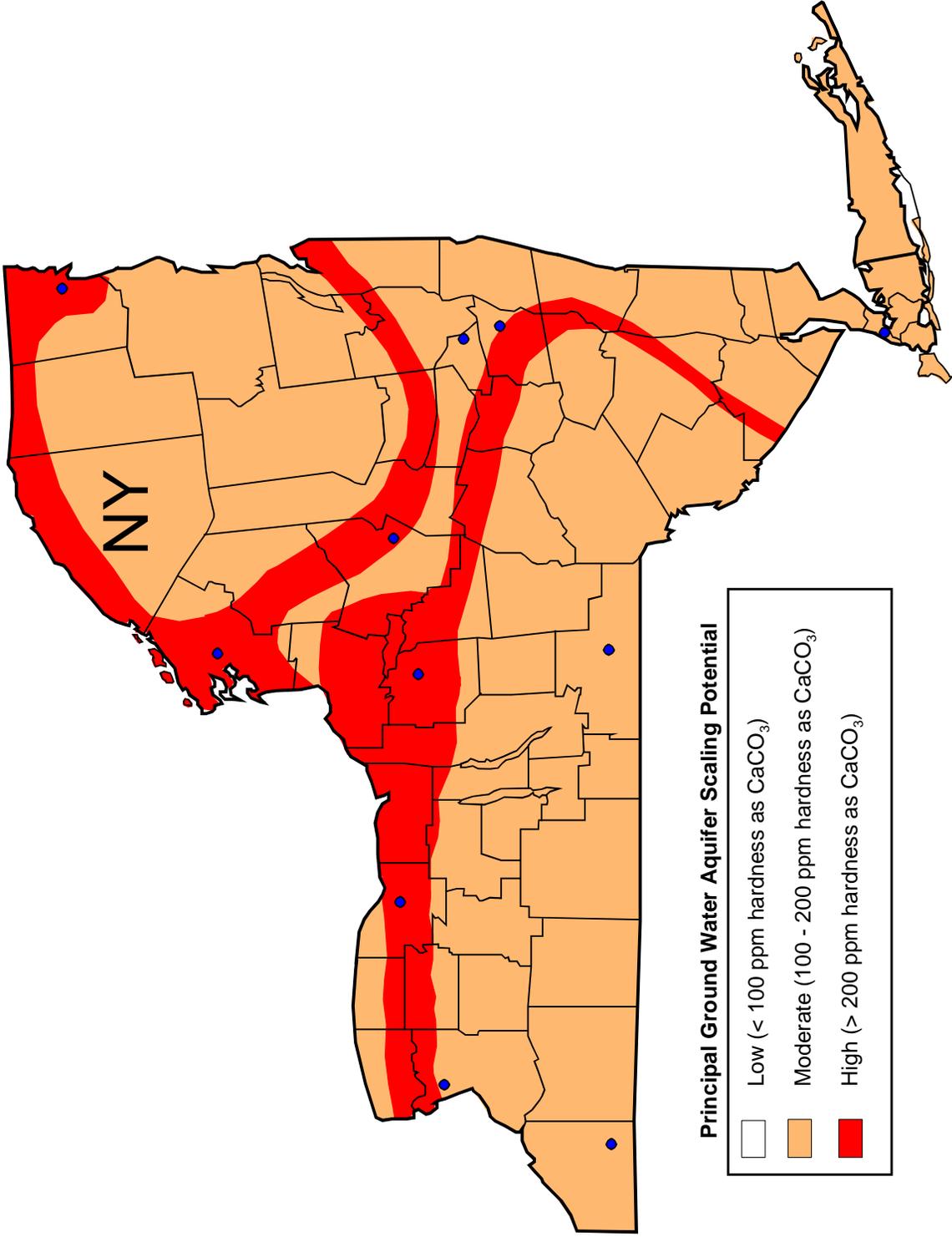


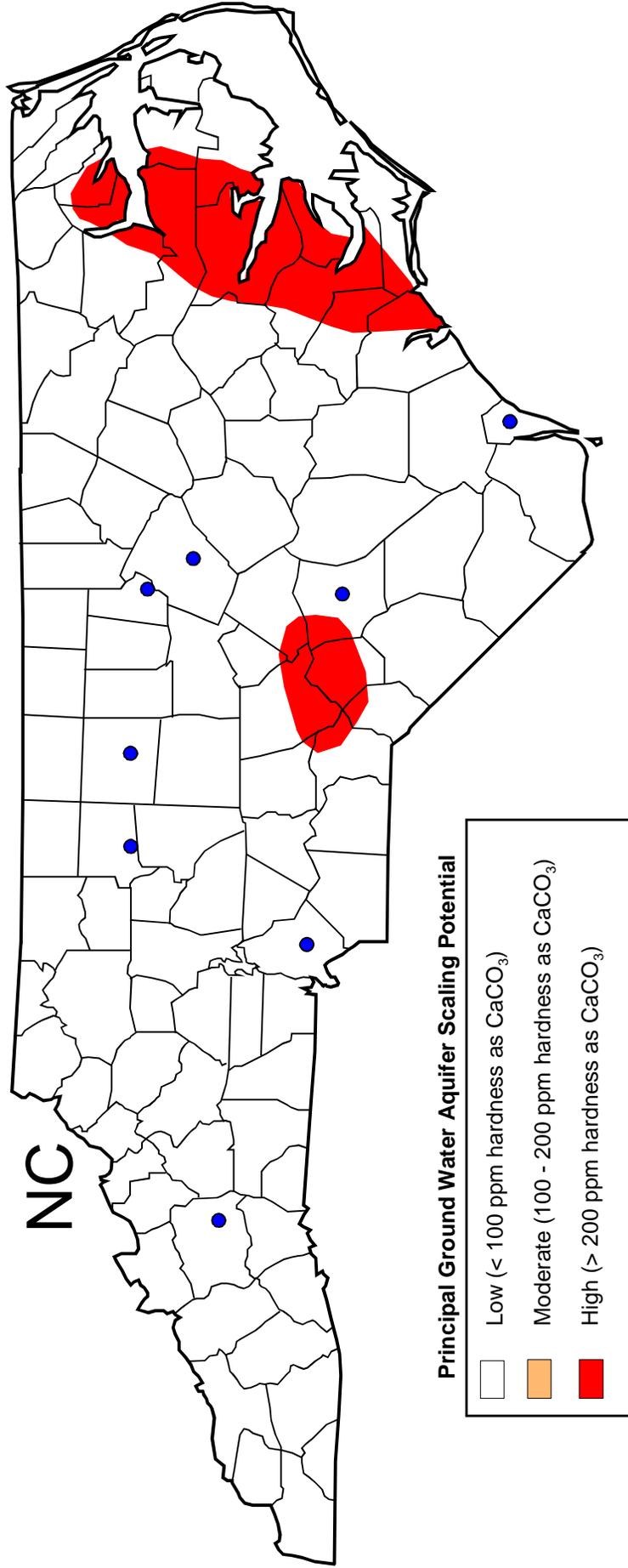


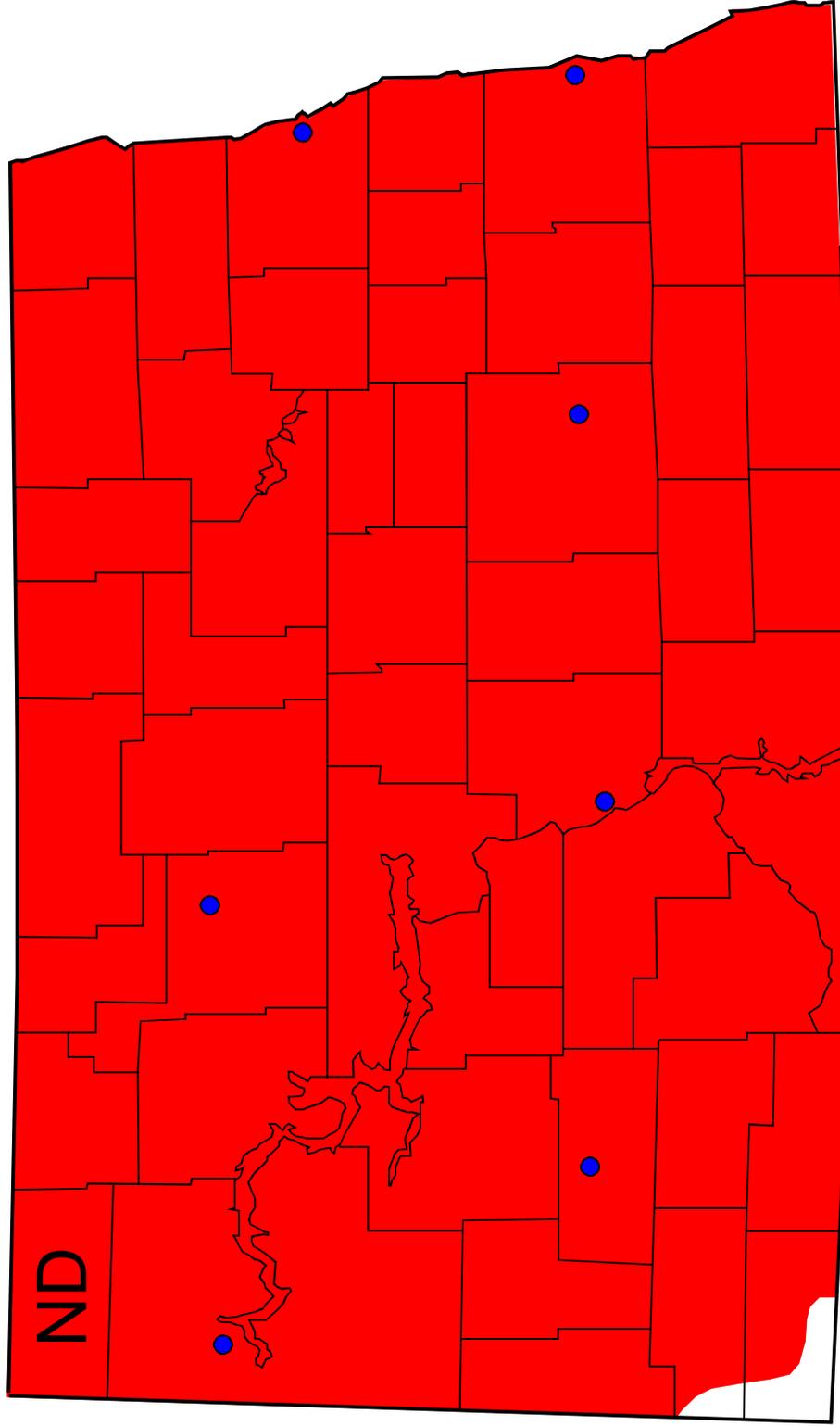
Principal Ground Water Aquifer Scaling Potential

-  Low (< 100 ppm hardness as CaCO₃)
-  Moderate (100 - 200 ppm hardness as CaCO₃)
-  High (> 200 ppm hardness as CaCO₃)



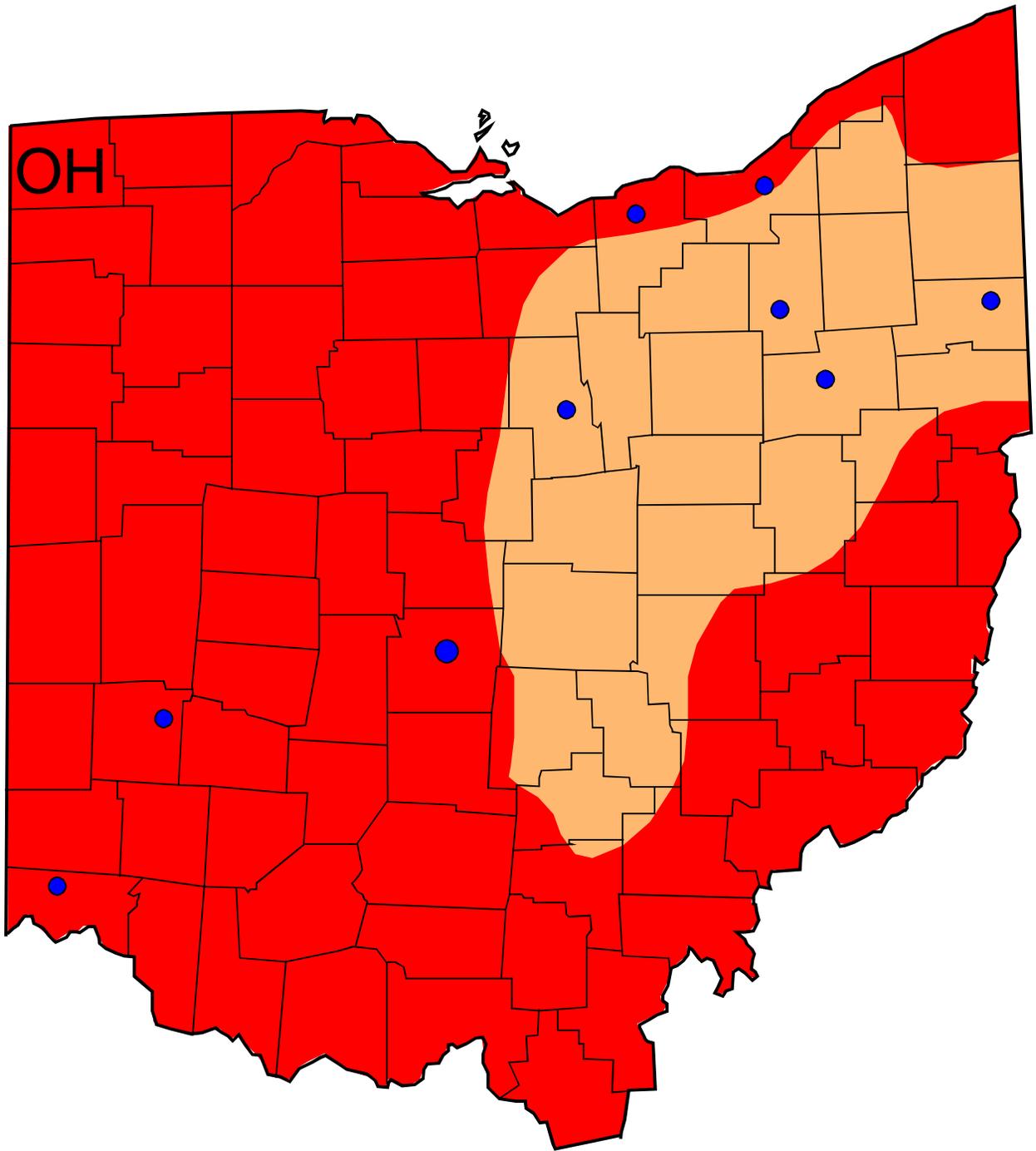






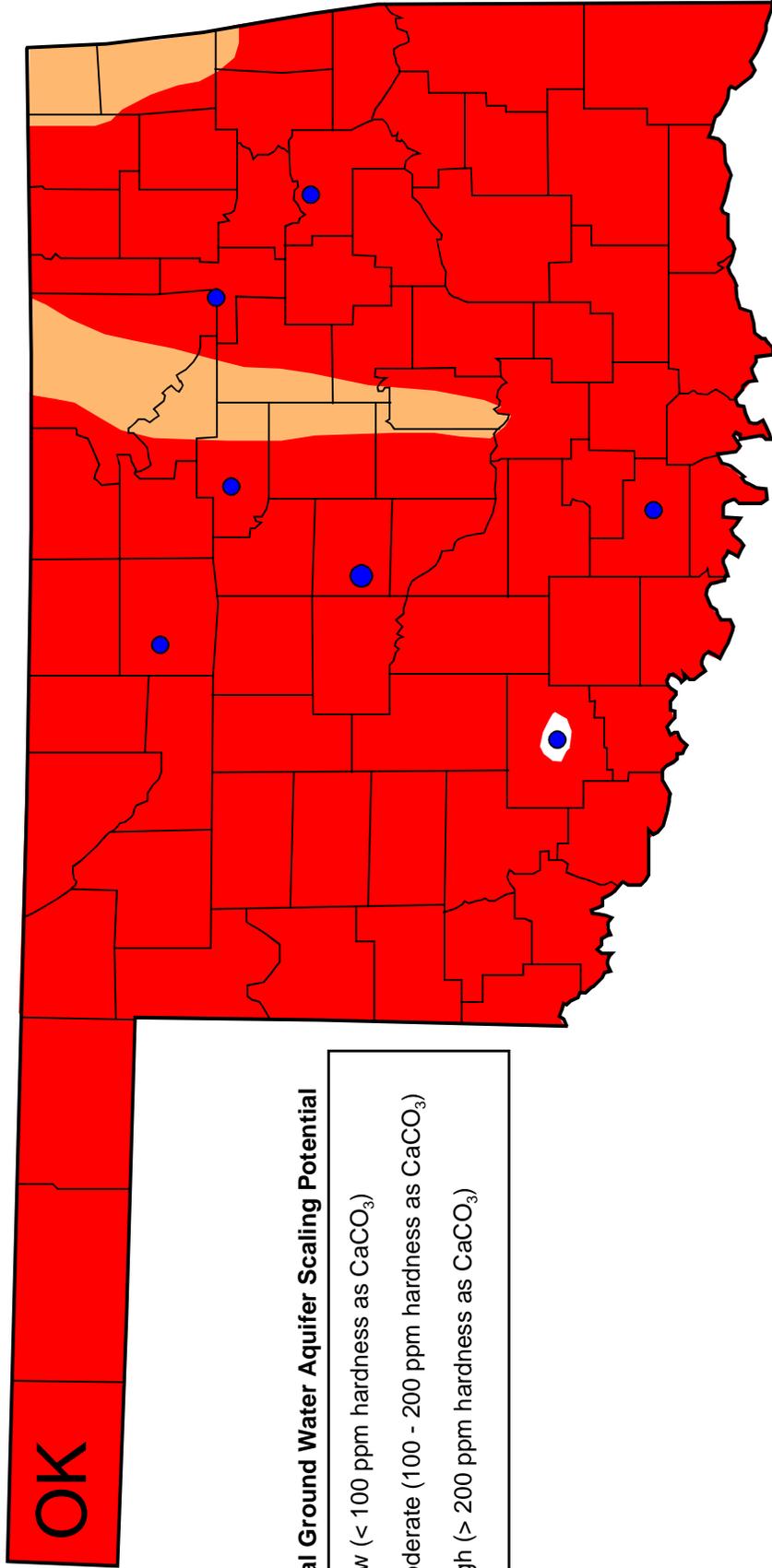
Principal Ground Water Aquifer Scaling Potential

- Low (< 100 ppm hardness as CaCO_3)
- Moderate (100 - 200 ppm hardness as CaCO_3)
- High (> 200 ppm hardness as CaCO_3)



Principal Ground Water Aquifer Scaling Potential

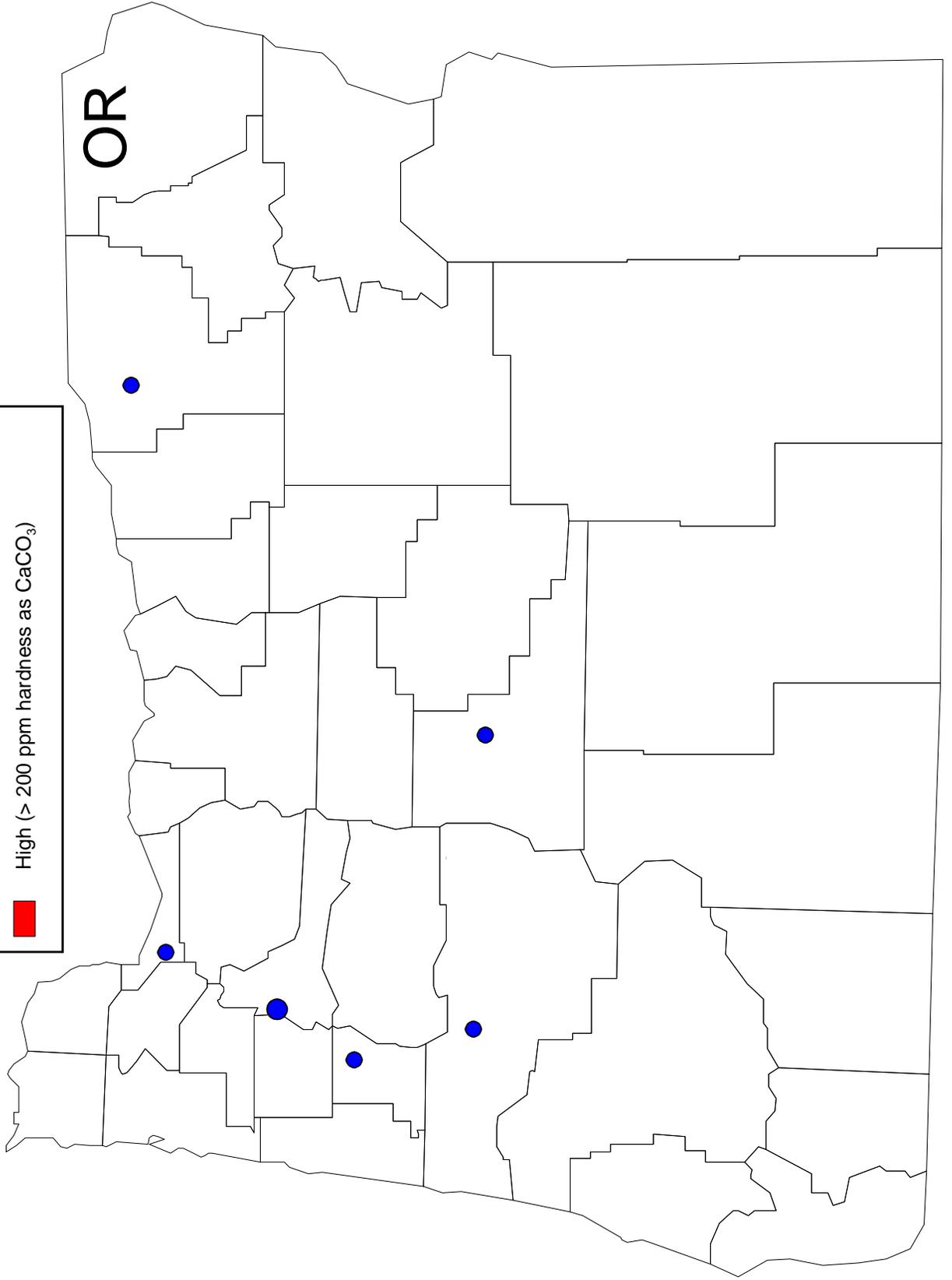
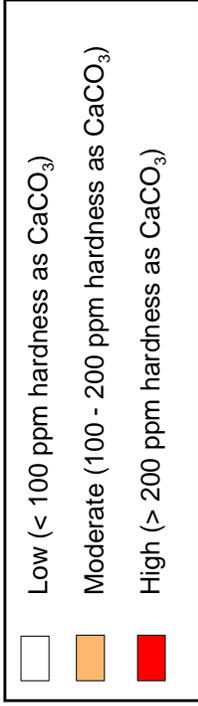
	Low (< 100 ppm hardness as CaCO ₃)
	Moderate (100 - 200 ppm hardness as CaCO ₃)
	High (> 200 ppm hardness as CaCO ₃)



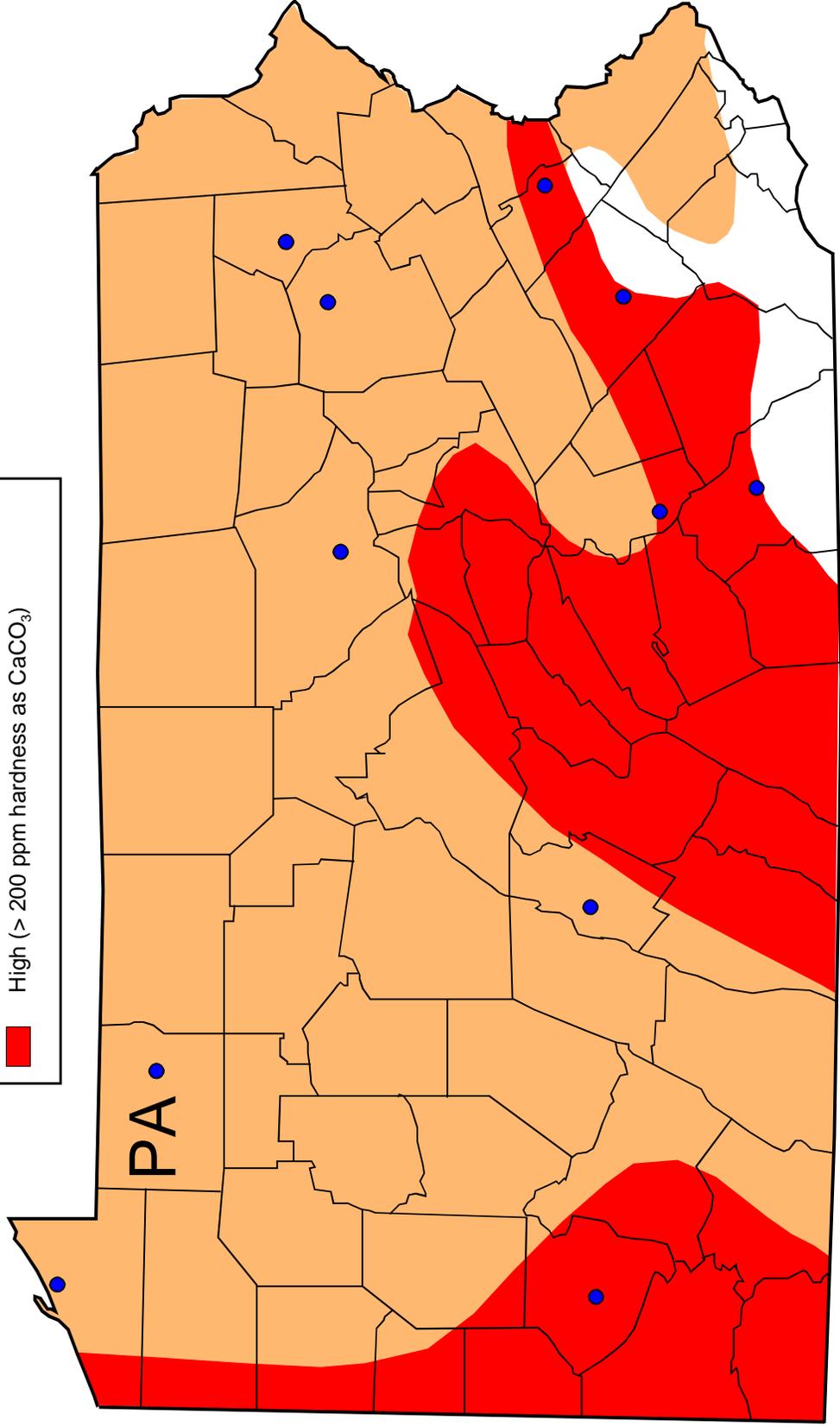
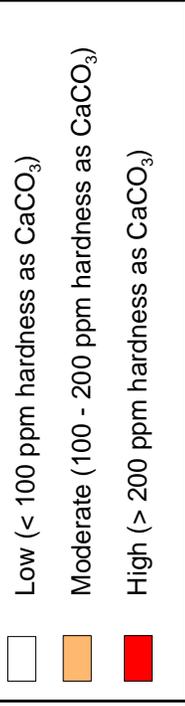
Principal Ground Water Aquifer Scaling Potential

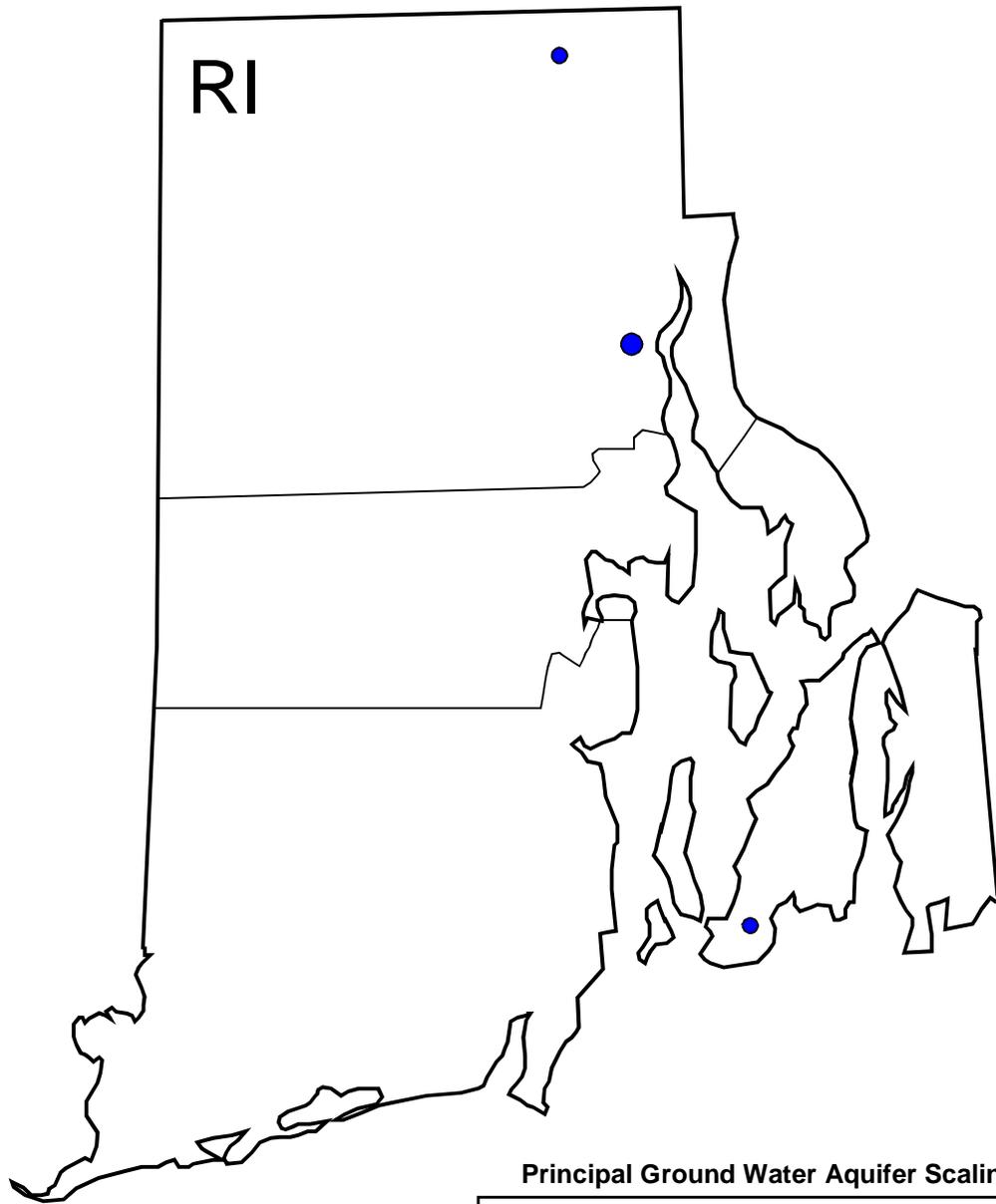
- Low (< 100 ppm hardness as CaCO₃)
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- High (> 200 ppm hardness as CaCO₃)

Principal Ground Water Aquifer Scaling Potential



Principal Ground Water Aquifer Scaling Potential

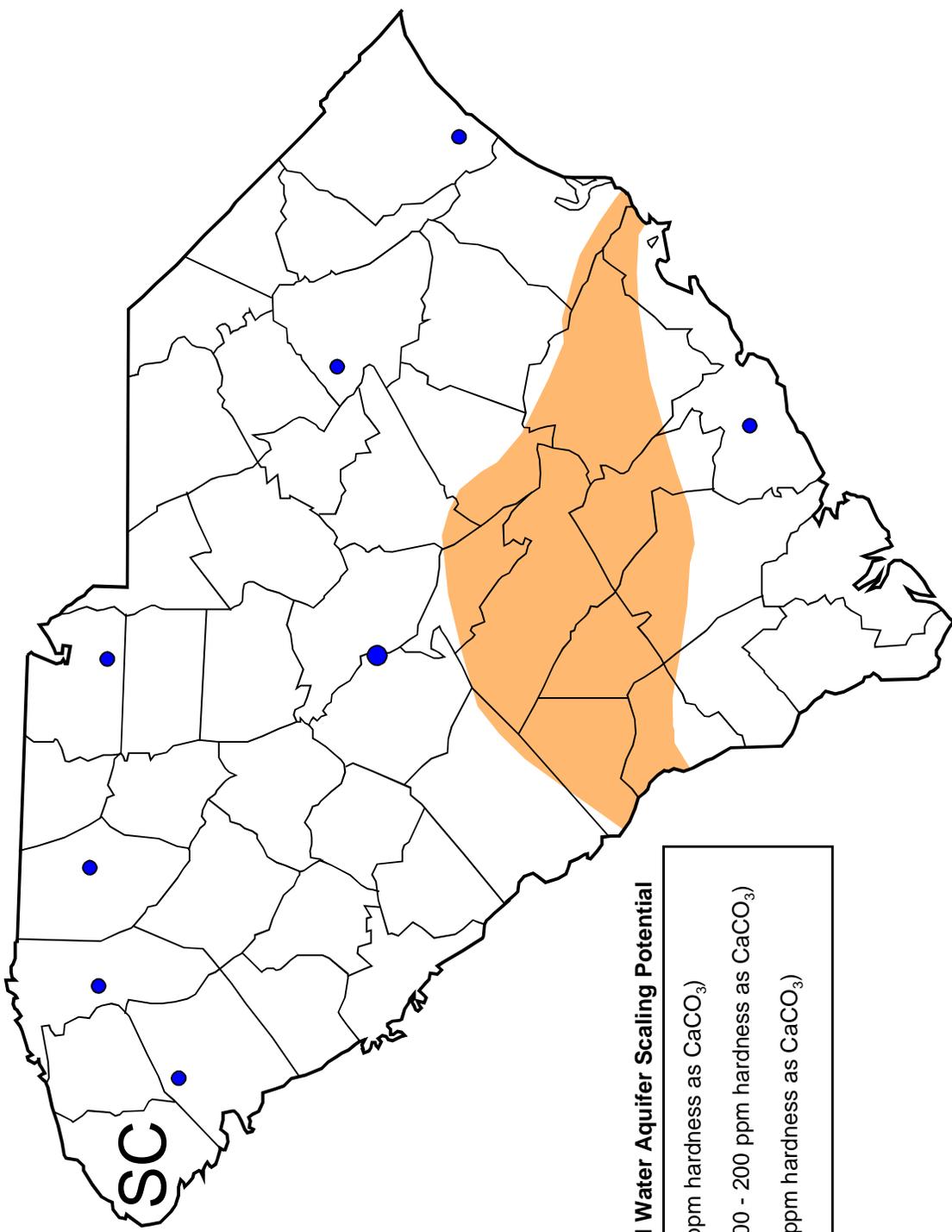




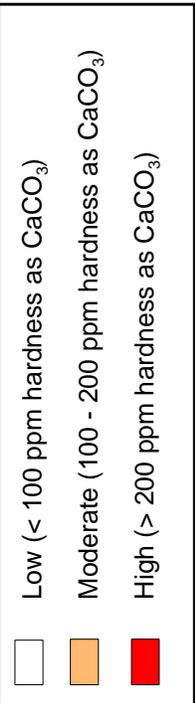
Principal Ground Water Aquifer Scaling Potential

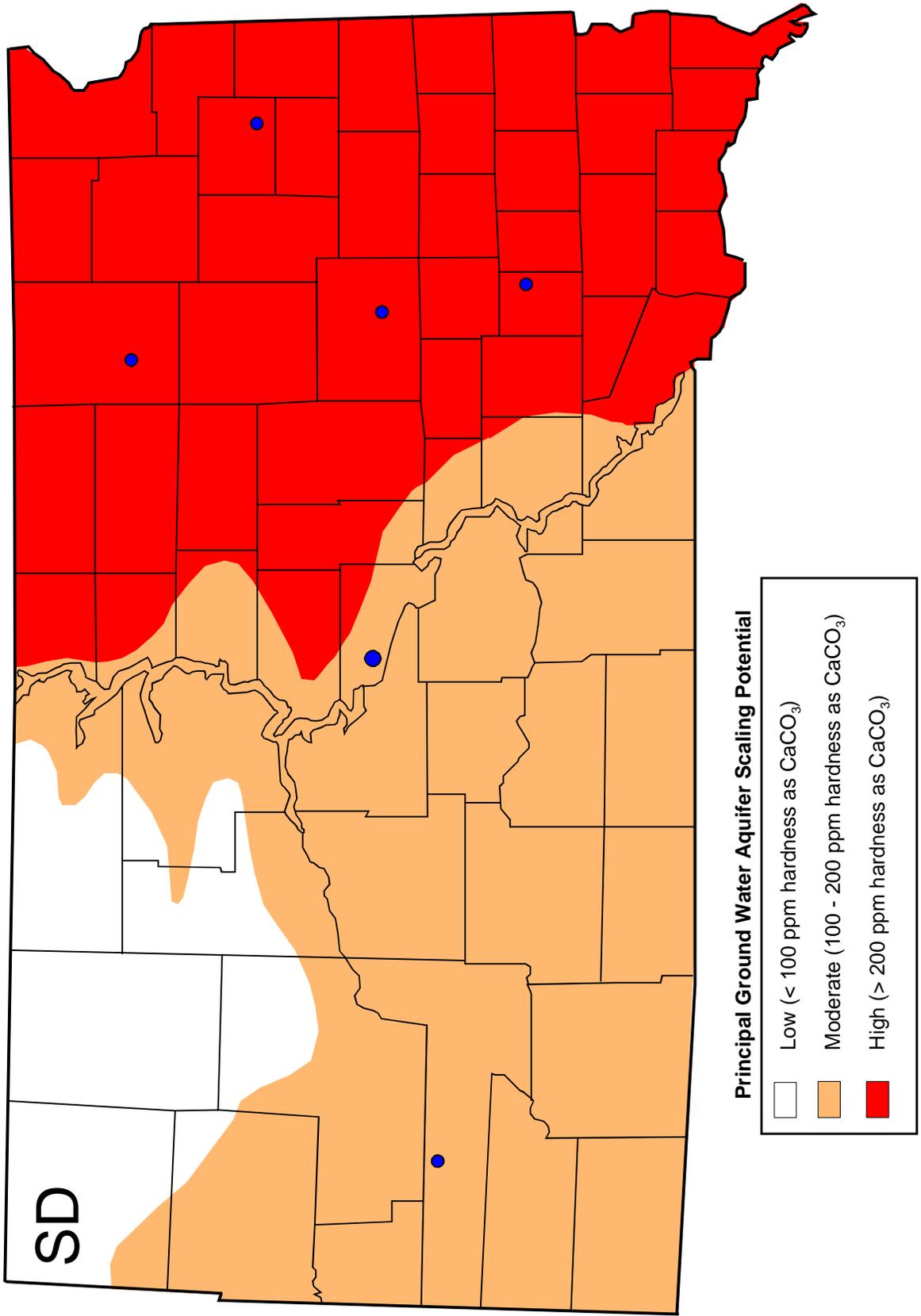
	Low (< 100 ppm hardness as CaCO ₃)
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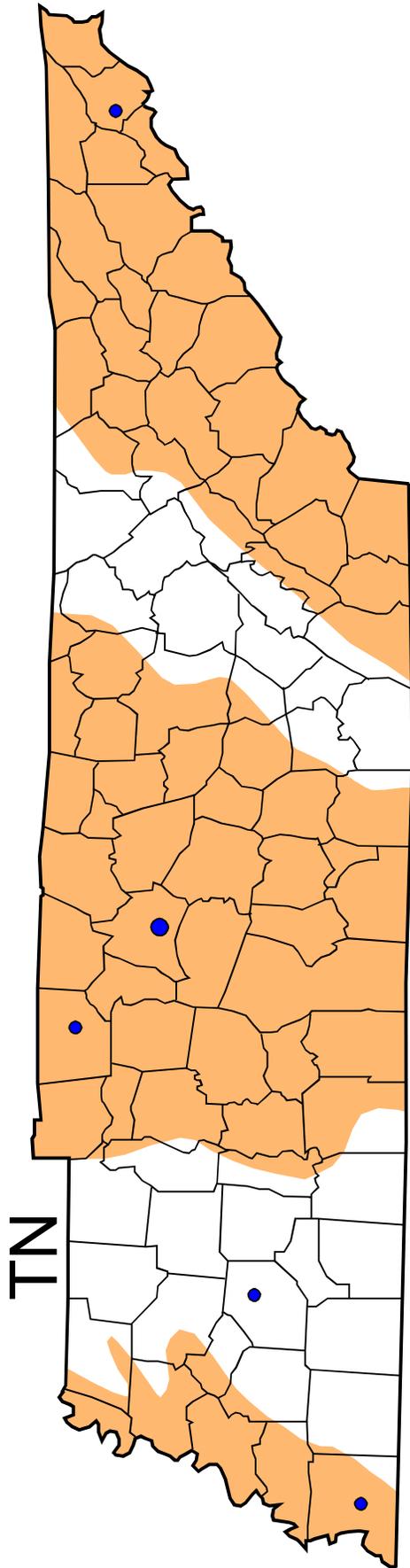




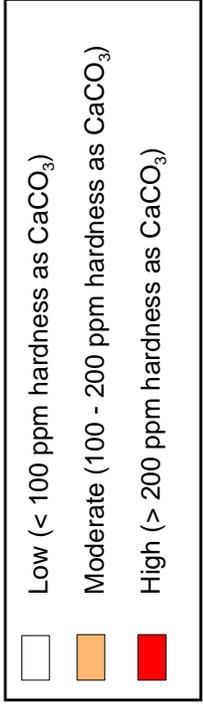
Principal Ground Water Aquifer Scaling Potential

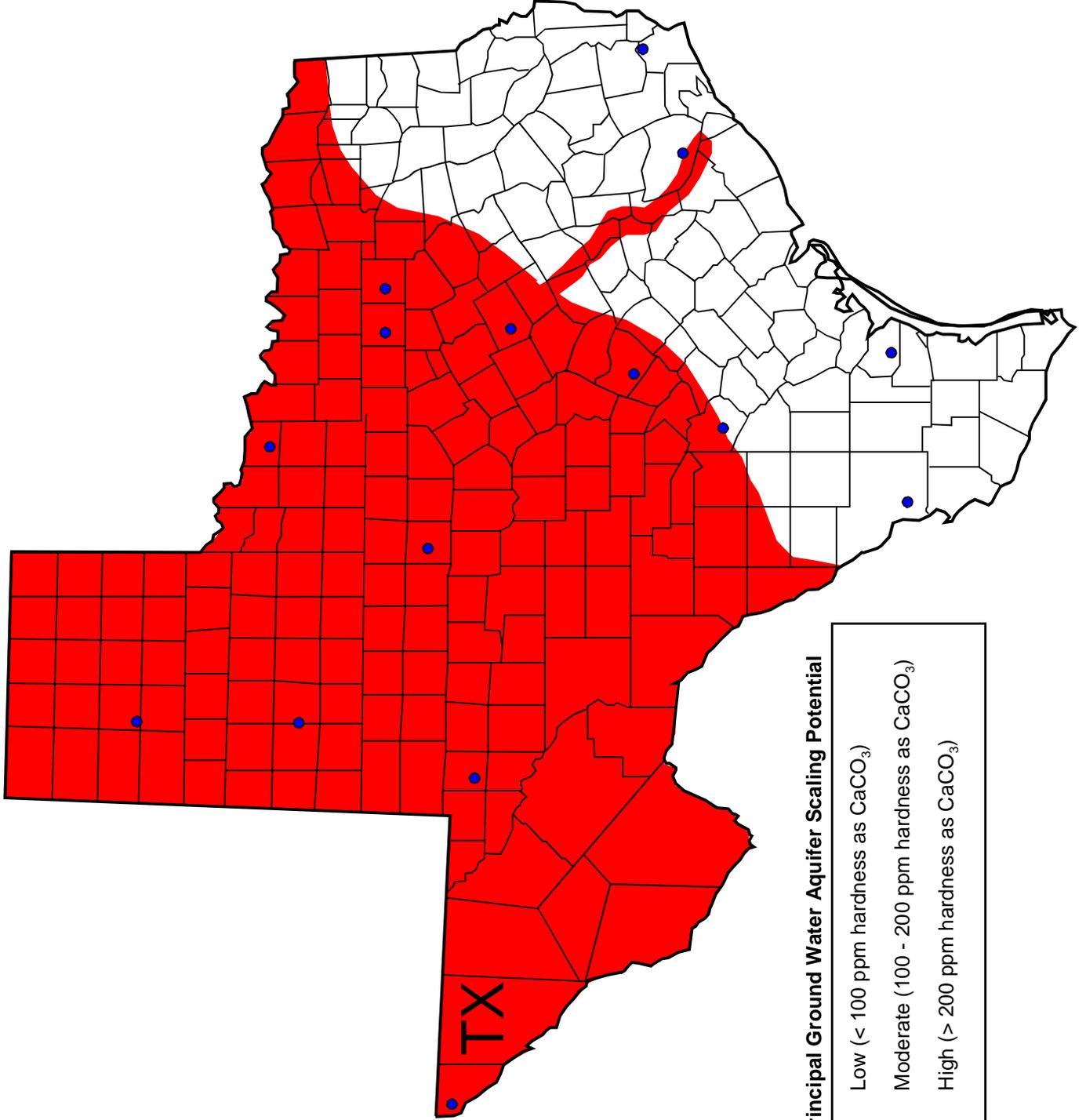






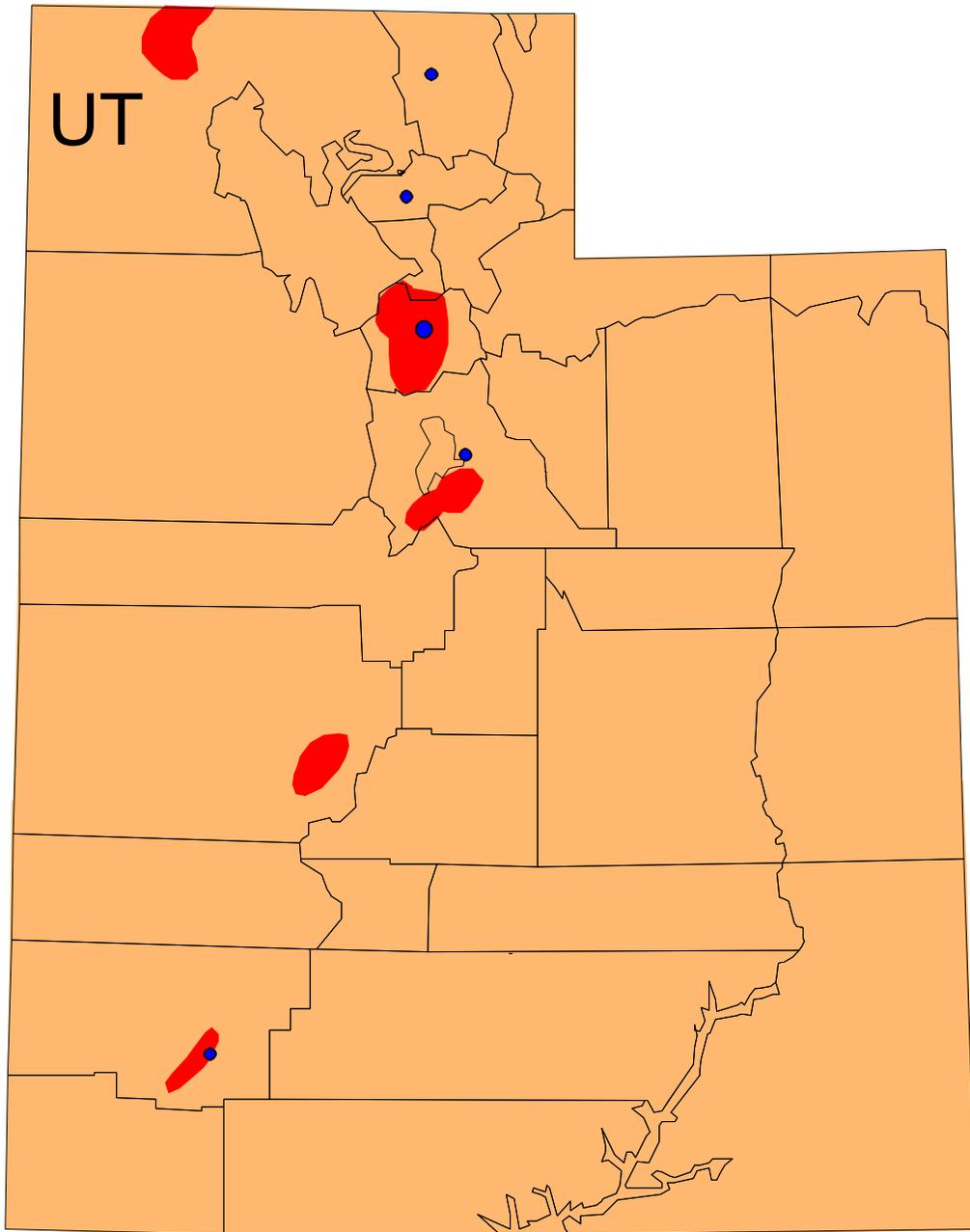
Principal Ground Water Aquifer Scaling Potential



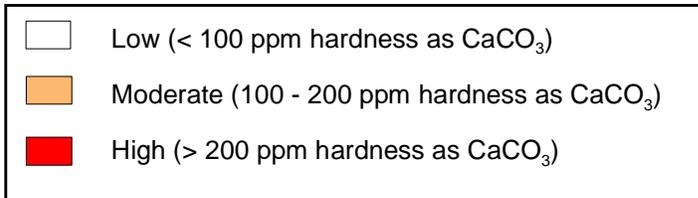


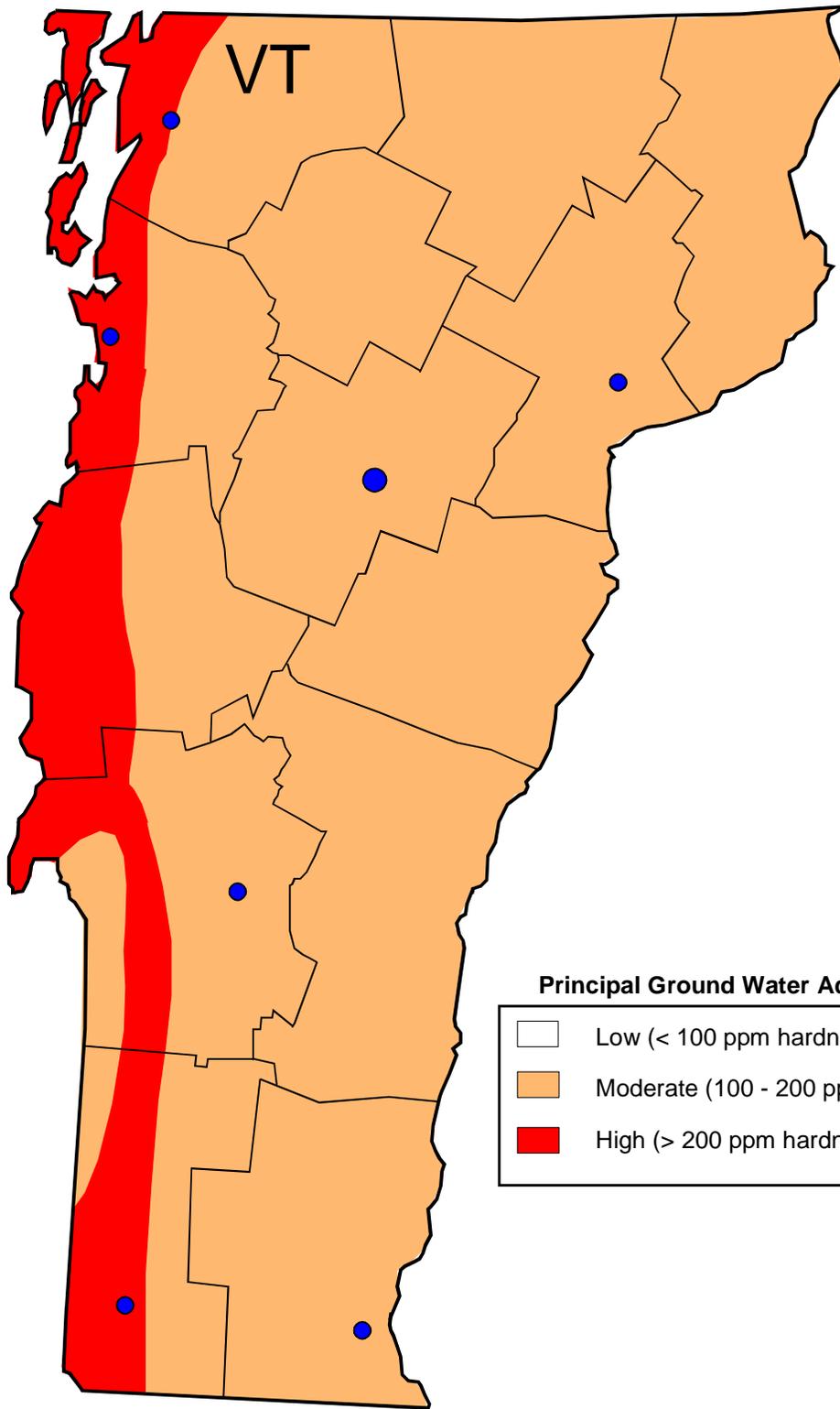
Principal Ground Water Aquifer Scaling Potential

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-  High (> 200 ppm hardness as CaCO₃)



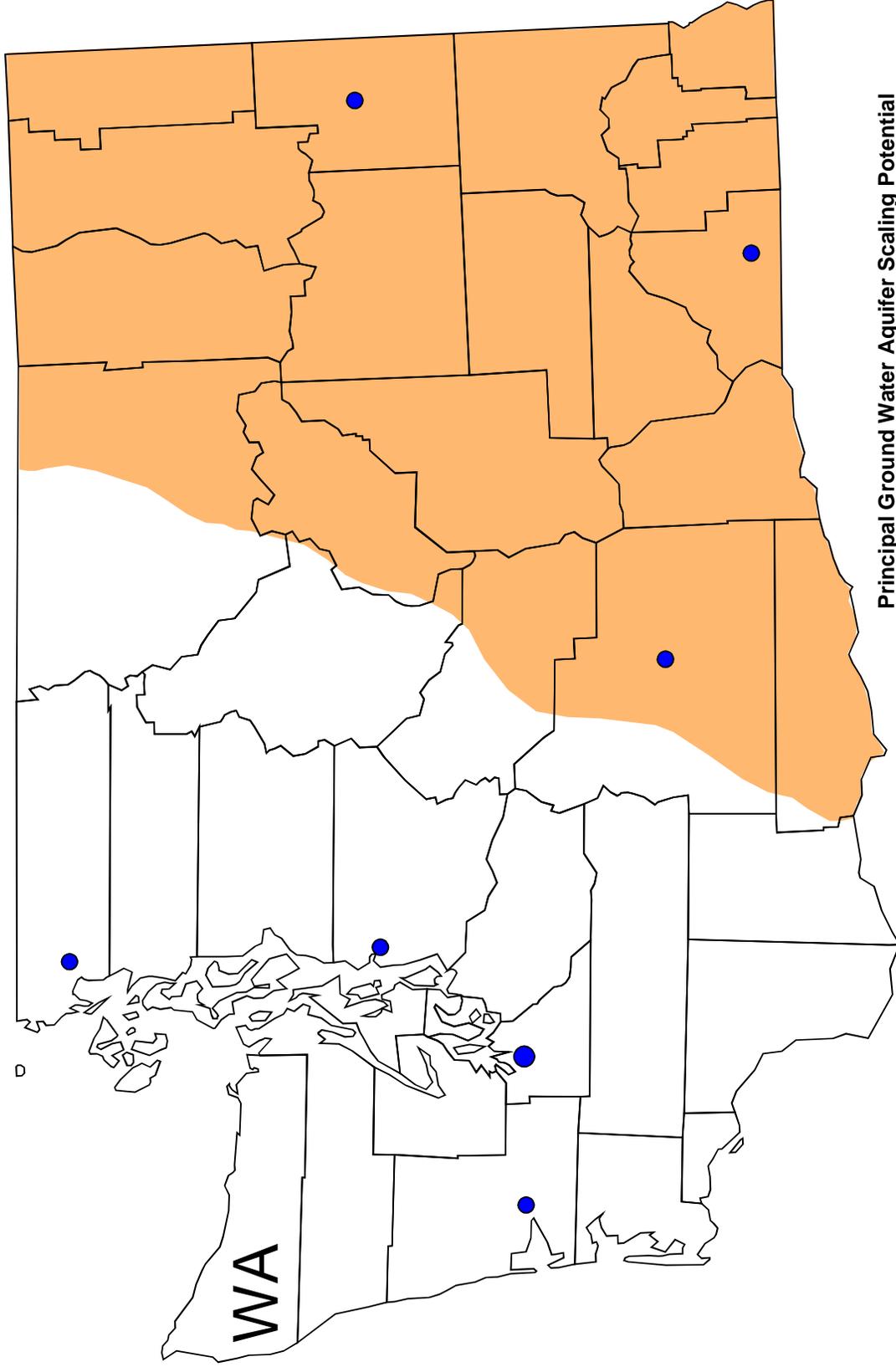
Principal Ground Water Aquifer Scaling Potential



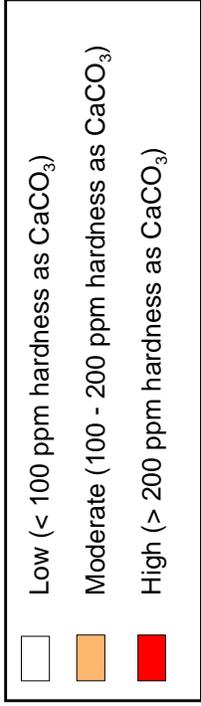


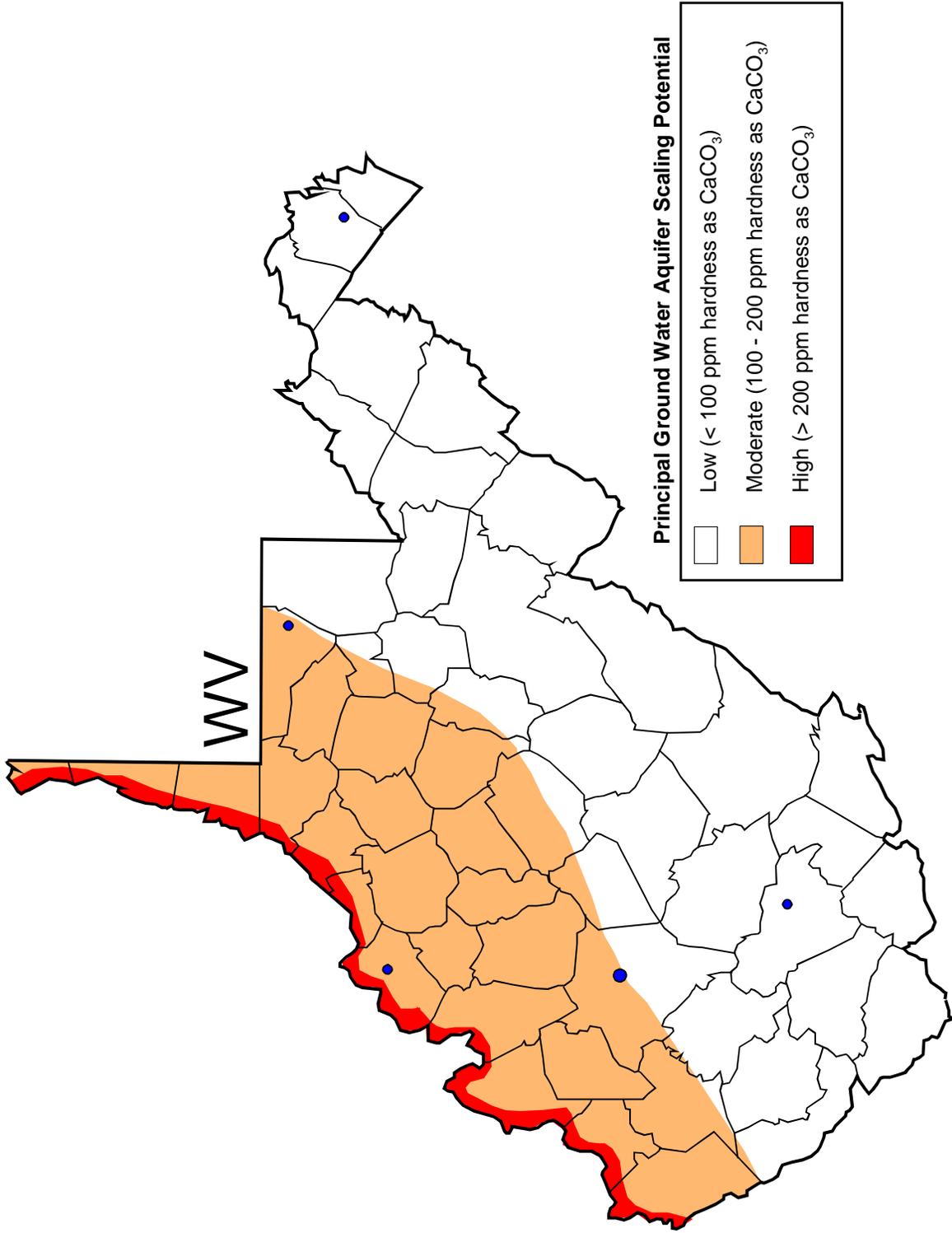
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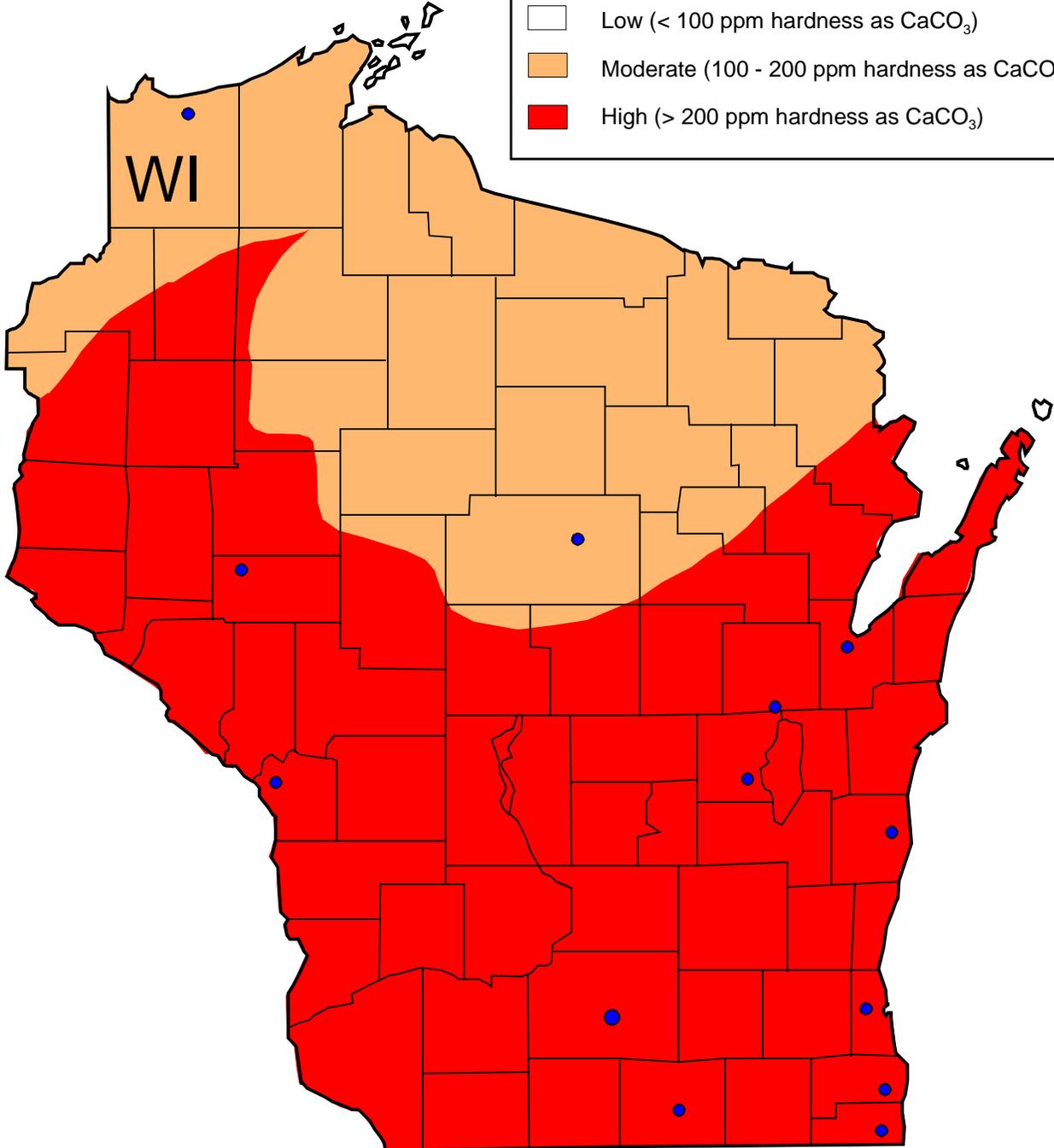
Principal Ground Water Aquifer Scaling Potential





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Principal Ground Water Aquifer Scaling Potential

