Appendix B: Rates and Densities of Natural Gas Well Development

The rate and ultimate density of natural gas well development in the NYC watershed will depend on a variety of economic, technical and regulatory factors. In order to characterize potential development scenarios in the watershed and the resulting cumulative impacts, historical rates and densities of drilling in other formations were evaluated. Sufficient data exists from other shale gas plays that have been under development for the last two to ten years to estimate reasonable ranges for rates and densities of well construction.

The rates and densities of natural gas well development in other major shale gas formations were characterized based on well completion and permitting data from state regulatory agencies and drill rig activity data from industry sources. Four major shale gas plays were identified for comparison purposes: Barnett (Texas), Fayetteville (Arkansas), Haynesville (Louisiana), and Marcellus (Pennsylvania). These formations are all gas-bearing tight shales that require hydraulic fracturing for economic production and have been developed using a combination of horizontal and vertical wells. This assessment focuses on the "Core" and "Tier I" areas within these formations, which are loosely defined in the natural gas industry as the areas that have the highest potential for gas production. Salient features of these formations and the Core/Tier I counties selected for comparison are summarized in Table B-1.

Table B-1: Representative Core/Tier I Counties of Major Shale Gas Plays

Formation (State)	Approximate # Years under Development	Total Formation Area (mi^2)	Selected Counties	Area (mi2)	% of Formation Area in Selected Counties
Barnett (TX) (Newark East field)	13 [28]	5,000	Denton, Johnson, Tarrant, Wise	3,512	70%
Fayetteville (AR) (B-43 field)	6	9,000	Cleburne, Conway, Faulkner, Van Buren, White	3,589	40%
Haynesville (LA)	3	9,000	Bossier, Caddo, De Soto, Red River	3,100	34%
Marcellus (PA)	2	95,000	Bradford, Lycoming, Susquehanna, Tioga	4,374	5%

Core and Tier I areas were selected as the basis of comparison because available data suggests that the NYC watershed is underlain by portions of the Marcellus with high gas production potential. Analysis of the depth, thickness, organic content, thermal maturity, and other characteristics of the Marcellus formation has been performed as part of an ongoing study by the New York State Museum.[29] Figure B-1, which is drawn from the NYS Museum study, shows the approximate depth to the top of the Marcellus formation (top portion) and the approximate

[28] The Newark East Barnett Shale field was discovered in 1981 but exploitation was low for nearly two decades due to technology limitations. The pace of well development accelerated dramatically in the late 1990s and early 2000s with the advent of water-based fracturing (1997).

[29] Smith, T. and J. Leone. New York State Museum. *Integrated Characterization of the Devonian Marcellus Shale Play in New York State*. Presented at the Marcellus Shale Gas Symposium of the Hudson-Mohawk Professional Geologists' Association, April 29, 2009. Accessed from www.hmpga.org/Marcellus_presentations.html.

thickness of the formation (lower portion). The dotted contours also indicate the transformation ratio associated with the formation, which is an estimate of the thermal maturity of the organic material.[30] The higher the ratio, the more gas that is potentially available.

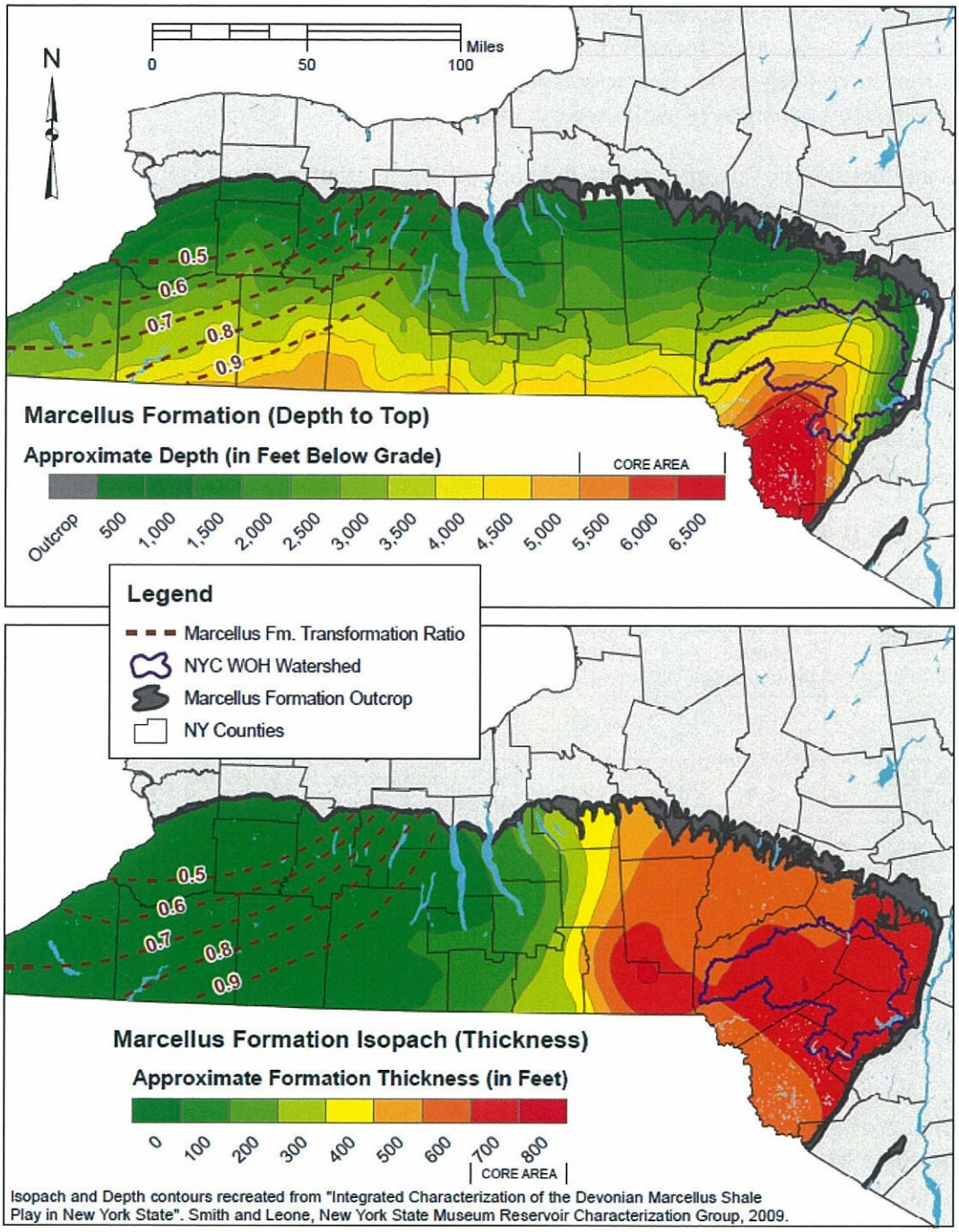

Figure B-1: Extent and characteristics of Marcellus formation in New York

[30] Transformation ratio refers to the percentage of Kerogen (an organic solid, bituminous mineraloid substance) occurring in the unit, that has been destructively converted to oil or gas by ambient geological forces (i.e., pressure, temperature).

While acknowledging uncertainties that prevent precise delineation of areas with the highest gas production potential, the authors of the study suggest that drilling in New York is likely to start in the thickest and deepest areas of the formation, which includes southern Tioga, Broome, Delaware and Sullivan Counties, which border the northeast corner of Pennsylvania, before progressing north and west. These areas are also attractive for gas production because of their proximity to the Millennium pipeline and other regional natural gas transmission infrastructure.

The supposition that the area identified in the New York State Museum study may be highly productive is supported by the intense leasing activity observed in this area and in neighboring counties in northeast Pennsylvania, as well as the ongoing development of a major regional drilling services facility in Horseheads (Chemung County), New York.

Well Completions

Well completion data provides a guide to the historical progression of the development of other shale gas plays and is useful in characterizing potential development scenarios in the NYC watershed area. Annual well completion rates in the selected Core/Tier I counties of the four major shale gas plays are presented in Figure B-2. Natural gas well completion data was derived from state regulatory agency databases and reports.[31] Well completion data was normalized to the area of the selected counties[32] to facilitate comparison among formations, and is expressed as number of wells per 1,000 square miles. The data does not include wells that have been permitted but not drilled.

Development of each of the plays has been characterized by an initial low rate of well completions as drilling and stimulation techniques are adapted to the formation. In the case of the Newark East Barnett Shale field, this period lasted nearly two decades after discovery of the field in 1981. The pace of Barnett well completion accelerated dramatically in the late 1990s and early 2000s with the advent of water-based fracturing (~1997) and horizontal drilling (~2003), and has continued to increase with successive improvements in extraction technology (e.g. improvements in chemical treatments, re-fracturing of existing wells, simultaneous fracturing of two or more adjacent wells).[33] Since 2002, well completion rates in the Barnett Newark East formation have grown from roughly 500 to 2,800 wells per year. On a unit area basis, these rates correspond to *annual* rates of 100 to 560 wells per 1,000 square miles.[34]

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[31] Marcellus data from Pennsylvania Department of Environmental Protection as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09). Haynesville data from Louisiana Department of Natural Resources SONRIS Well Data as of 10/23/09 (http://dnr.louisiana.gov/haynesvilleshale/haynesville.xls, accessed 11/1/09). Fayetteville data from Arkansas Oil and Gas Commission B-43 Field Well Completions as of 10/30/09 (http://www.aogc.state.ar.us/Fayprodinfo.htm, accessed 11/1/09). Barnett data from Texas Railroad Commission as of 9/8/09 (http://www.rrc.state.tx.us/barnettshale/barnettshalewellcount1993-2008.pdf, and http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf, accessed 11/1/09).

[32] County-level annual data is not readily available for the Barnett shale; data in Figure B-2, Figure B-3, and Figure B-5 is based on the entire Newark East formation and is normalized to a nominal formation area of 5000 mi^2. Actual well density in core counties is higher (see e.g. Figure B-4).

[33] Powell, M.E. (2009). *Recent Developments in the Barnett Shale*, presented at Texas Alliance of Energy Producers 2009 Alliance Expo & Annual Meeting, 4/22/09.

[34] Low Barnett completion rates in 2009 reflect in part a substantial drop in natural gas wellhead prices since their peak in mid-2008.

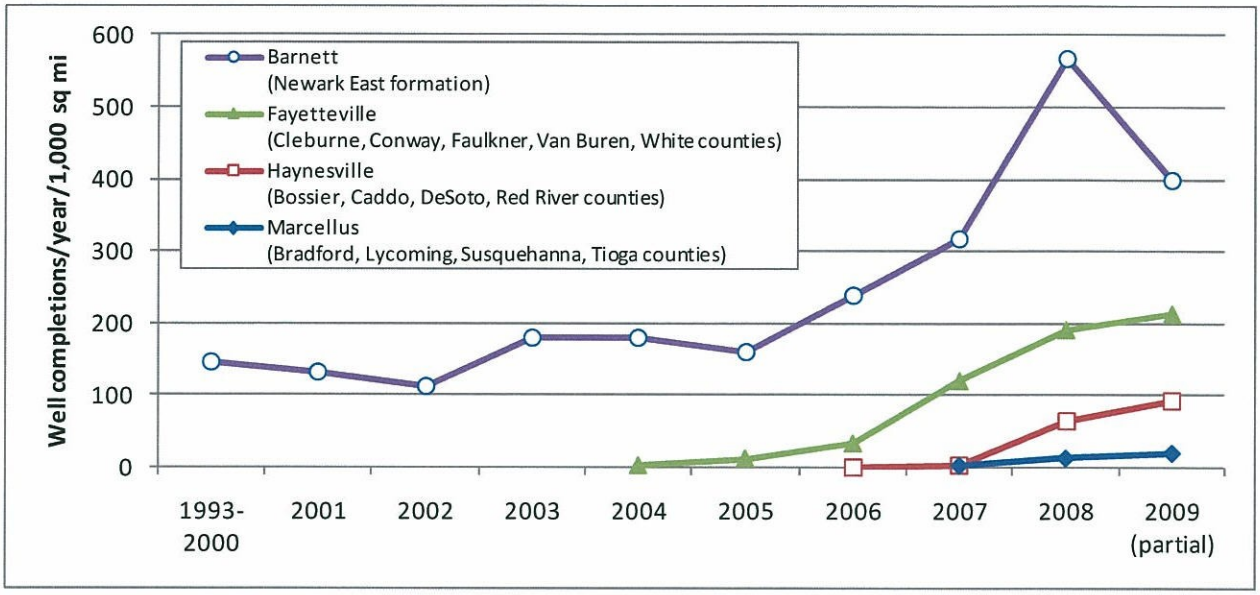

Figure B-2: Annual Well Completion Rates in Core/Tier I Counties of Major Shale Gas Plays

Based in large part on adoption of mature horizontal drilling and hydraulic fracturing techniques from the nearby Barnett formation, the rate of well completion in the Fayetteville formation B-43 Field increased rapidly, from 10 wells in 2004 to 430 wells in 2007 (3 – 120 wells/yr/1,000 mi^2). From January 2009 to October 2009, over 760 wells were completed in the Fayetteville B-43 core counties. A similar rapid increase in development rates is observed in the Haynesville formation, where roughly 200 wells were completed in 2008, compared to nine wells in 2007 and one well in 2006. In the Marcellus formation in northeastern Pennsylvania, nine completions were recorded in 2007, 55 in 2008, and 88 through September 2009.

Evaluation of well completion data on a cumulative basis (Figure B-3) tracks the increase in well density that occurs as a formation is developed. The current density in the Marcellus northeastern Pennsylvania core counties is on the order of 35 wells per 1,000 square miles, as this play is at an early, exploratory phase of development in the selected counties.

The current density of the Fayetteville core counties after approximately six years of activity is about 570 wells per 1,000 square miles. Well density in the Barnett Newark East formation after 13 years of development has reached 2,400 wells per 1,000 square miles across four core counties, and has exceeded 3,000 wells per square mile in one county. Well development rates in the Barnett were increasing through 2008, suggesting that the play is still not fully developed.

These rates and densities are considered indicative of the overall spatial well density that could be expected in the NYC watershed area as development in the play progresses.[35] Current county-level density for the selected formations and core counties is summarized in Figure B-4.

[35] The NYC West of Hudson watershed has an area of 1585 mi^2, roughly two-thirds of which (~1000 mi^2) is not subject to constraints on natural gas well development (Section 3.2).

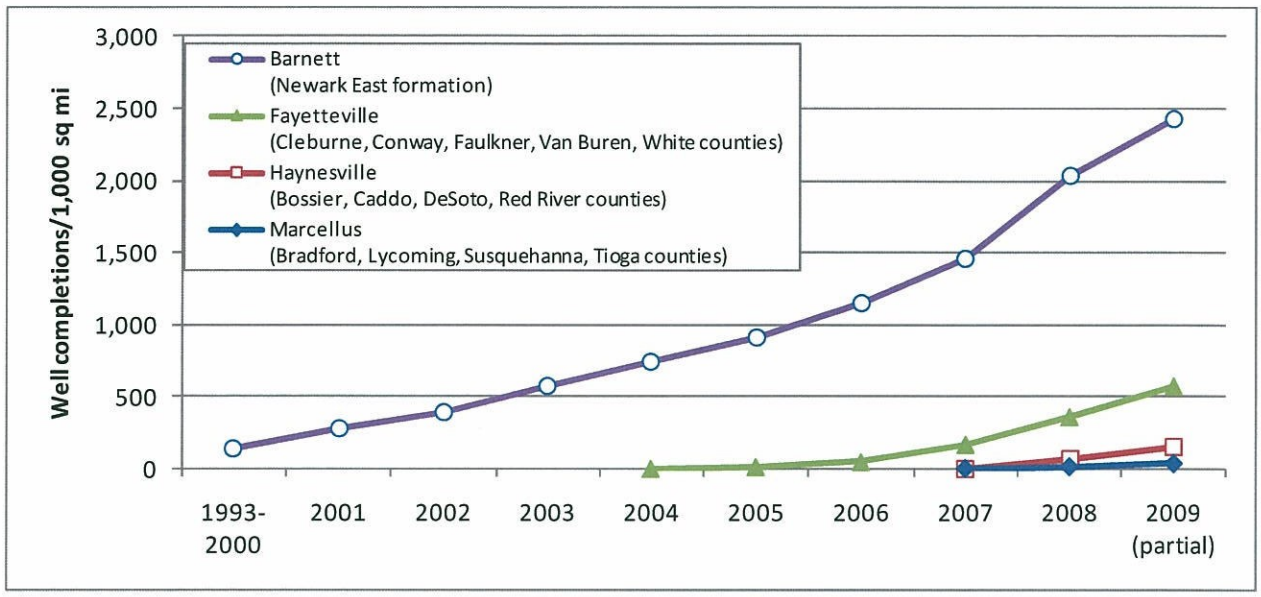

Figure B-3: Well Density in Core/Tier I Counties of Major Shale Gas Plays (2001-2009)

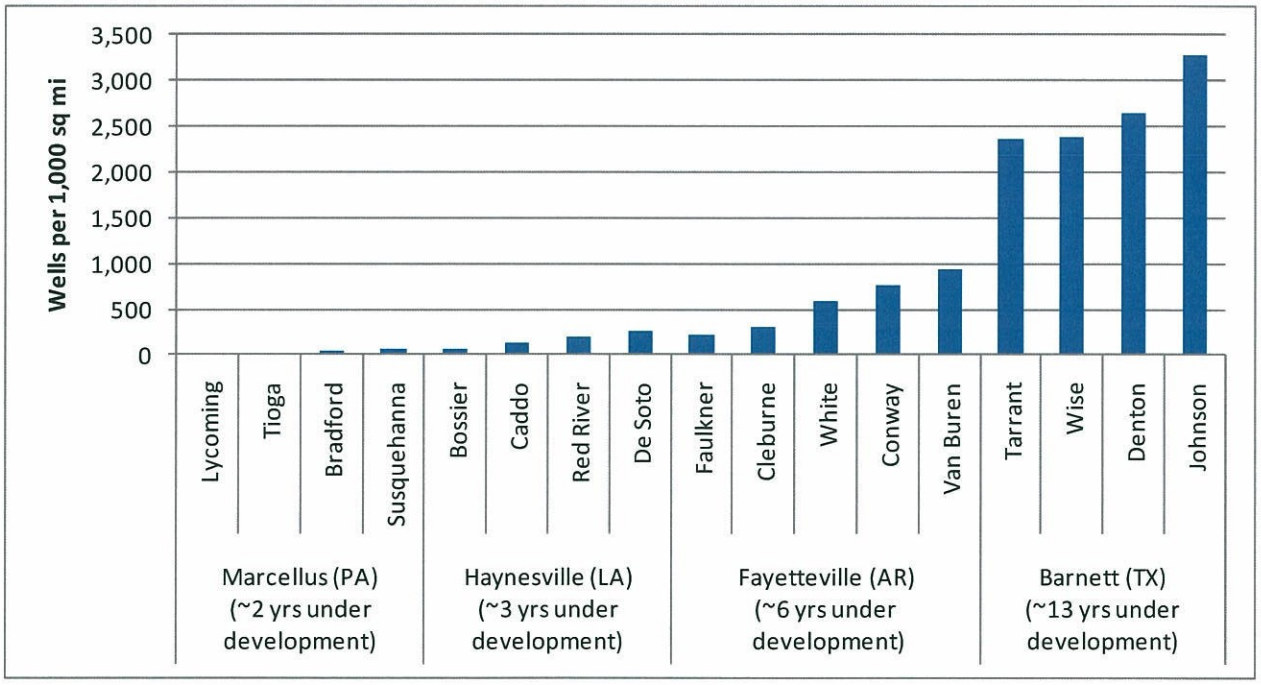

Figure B-4: Well Density in Core/Tier I Counties of Major Shale Gas Plays (2009)[36]

Well Permit Approvals

Wells must be permitted before they can be developed; a backlog of approved permits reflects the industry's understanding of future development potential in a given region and indicates

[36] All data sources identical to Figure B-2 except for the Barnett. County-level Barnett well information is based on data through 2008 presented in Powell, M.E. (2009). *Recent Developments in the Barnett Shale*, presented at Texas Alliance of Energy Producers 2009 Alliance Expo & Annual Meeting, 4/22/09.

likely near-term development. Annual well permitting rates for Core/Tier I counties of major shale gas plays are presented in Figure B-5. In some cases the backlog of permits can indicate substantial amounts of planned well development: in the Barnett, roughly three-quarters of the permits issued in the Barnett formation had been drilled as of August 2009, leaving over 3,500 approved permits awaiting development.[37]

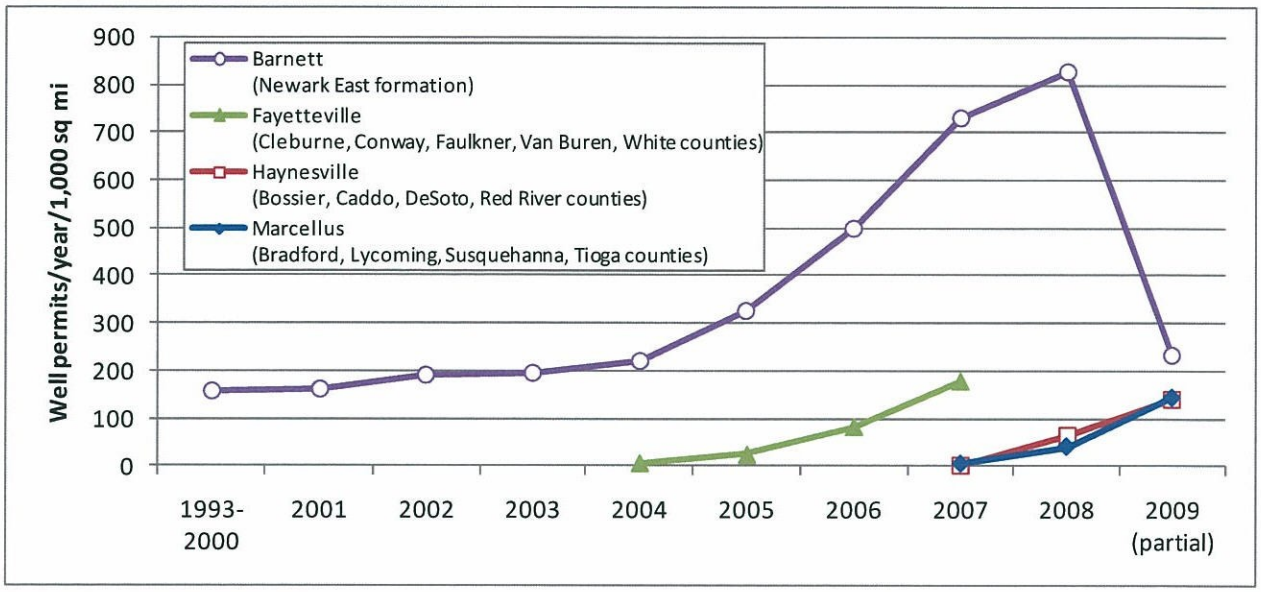

Figure B-5: Annual Well Permitting Rates in Core/Tier I Counties of Major Shale Gas Plays[38]

Data from northeastern Pennsylvania Marcellus counties (Figure B-6) also indicate the likelihood of sustained development in the region: of the roughly 800 permits approved since 2007, approximately 650 (~80 percent) await development. The greatest number of permits (approximately 340 through September 2009) have been filed in Bradford County, which at 1,151 square miles, covers an area equivalent to 73 percent of the entire area of NYC's West-of-Hudson watersheds.

As economic conditions improve and extraction techniques continue to be adapted to the regional geology, the rate of well development in the region can be expected to increase. Rotary drill rig[39] activity reveals the number of wells under development at any given time and is indicative of the natural gas industry's current and potential future level of activity in an area. Rotary drill rig activity over the past two years (Figure B-7) indicates that the pace of development in the Marcellus core counties is increasing, despite the economic downturn and low gas prices. Currently there are 30 to 35 rigs operating in the Marcellus core counties,

[37] Texas Railroad Commission (http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf, accessed 11/1/09).

[38] Data sources as described in Figure B-2, with the exception of the Fayetteville shale. Permitting dates are not readily available from the Arkansas Oil and Gas Commission; data presented in Figure B-5 is based on *Projecting the Economic Impact of the Fayetteville Shale Play for 2008-2012* (University of Arkansas, Center for Business and Economic Research, March 2008).

[39] Rotary drill rigs are the only types of rigs capable of horizontal drilling and are the most common type of rig used for oil and gas development.

compared with one rig at this time last year. The high levels of rig activity in the Barnett core in 2007-2008 (i.e. 120 rigs active at a given time) also indicate that the rate of development in the Marcellus is unlikely to be limited by industry drilling capacity.

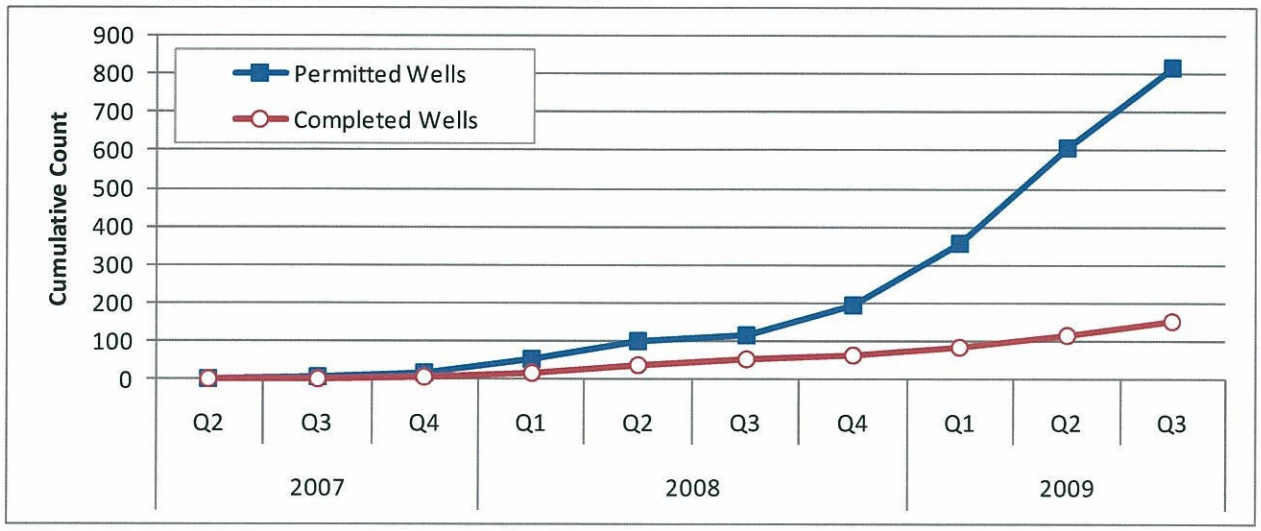

Figure B-6: Comparison of Marcellus formation well completion and permitting data (Bradford, Lycoming, Susquehanna and Tioga counties, Penna.)

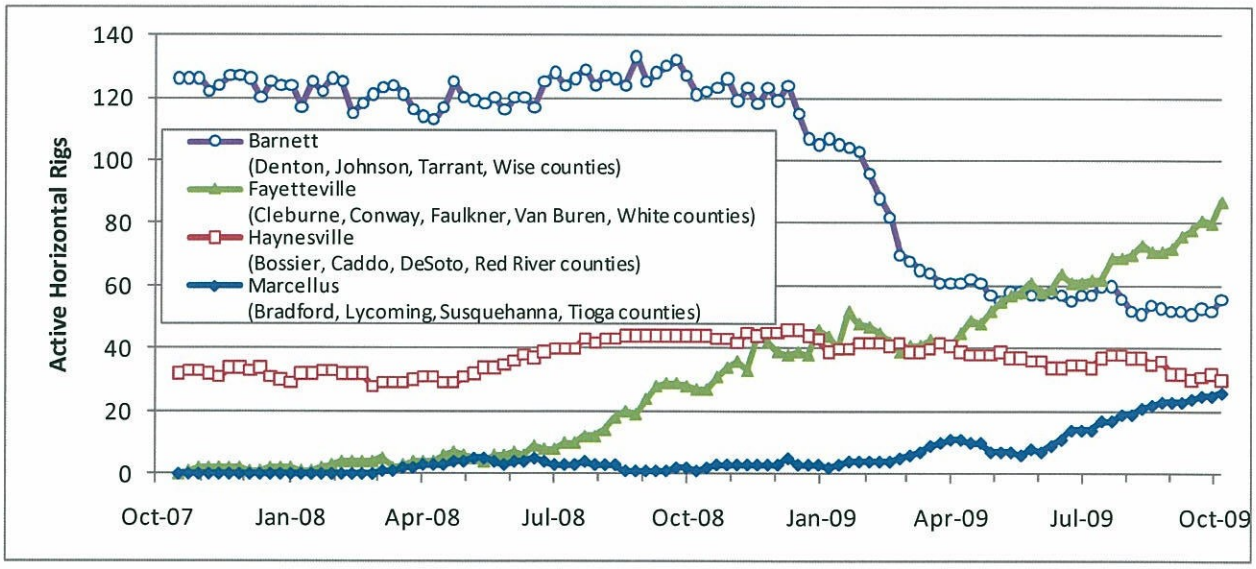

Figure B-7: Horizontal Drill Rig Activity in Core/Tier I Counties of Major Shale Gas Plays[40]

Distribution of Permitted and Completed Wells in other Formations

The geospatial distribution of wells is presented below for core areas of the Marcellus (Figure B-8), Haynesville (Figure B-9), Fayetteville (Figure B-10), and Barnett (Figure B-11). Marcellus

[40] Weekly county-level horizontal drill rig data from Baker Hughes U.S. Rig Count Reports (http://gis.bakerhughesdirect.com/Reports/RigCountsReport.aspx)

and Haynesville data is color-coded to reflect progression in the rate of development from 2007 through 2009. Permitting data is also presented where available.

In reviewing the spatial distribution of wells, it is clear that formations do not conform to political boundaries and wells are typically clustered in areas of high productivity; therefore, actual densities in some areas are much higher than the county average values presented above. Denton County in Texas, for example, has approximately 2,200 completed wells over a 400 square mile area, resulting in a localized density of twice the average for the county. It is important to note that given the scale of these figures, many of the plotted permit and gas well locations are obscured by neighboring symbols, thus a count of the visible symbols would yield a low estimate of actual activity.

Mapping of natural gas exploration activities in the Marcellus formation in eastern Pennsylvania reveal an accelerating rate of well construction over the two-year period from 2007 to 2009, as shown in Figure B-12. NYSDEC Notice of Intent to issue well permits in neighboring portions of New York State are also shown. It is reasonable to expect that the pattern and pace of development that could occur in New York State would be similar to that experienced in eastern Pennsylvania. It is important to note that the level of well development shown in Figure B-12 reflects the very early stages of development of the formation, and that a roughly one order of magnitude increase in well density should be anticipated.

Summary

Rates of natural gas well development in the comparable major shale gas formations provide the basis for the scenarios presented in Table B-2 and are consistent with well development patterns observed to date. Therefore, the scenarios provided are reasonable for estimating potential impacts within the NYC watershed even though the actual rate of development is uncertain due to numerous factors, including natural gas prices, regional economic conditions, state regulations, and formation productivity.

Table B-2: Annual Natural Gas Development Scenarios

Rate Scenario	Average Annual Well Completions per 1,000 Square Miles	Description
Low	20	Drilling rate during the early years of the play as operators refine their understanding of the resource and continue to lease land and apply for permits.
Moderate	100 to 300	Rate of well completion that has been sustained for a number of years in other shale gas plays
High	500, based on well completions (potentially as high as 800, based on permit applications)	Rate of development that could potentially occur in the most profitable areas under favorable conditions (e.g., gas prices are very high).

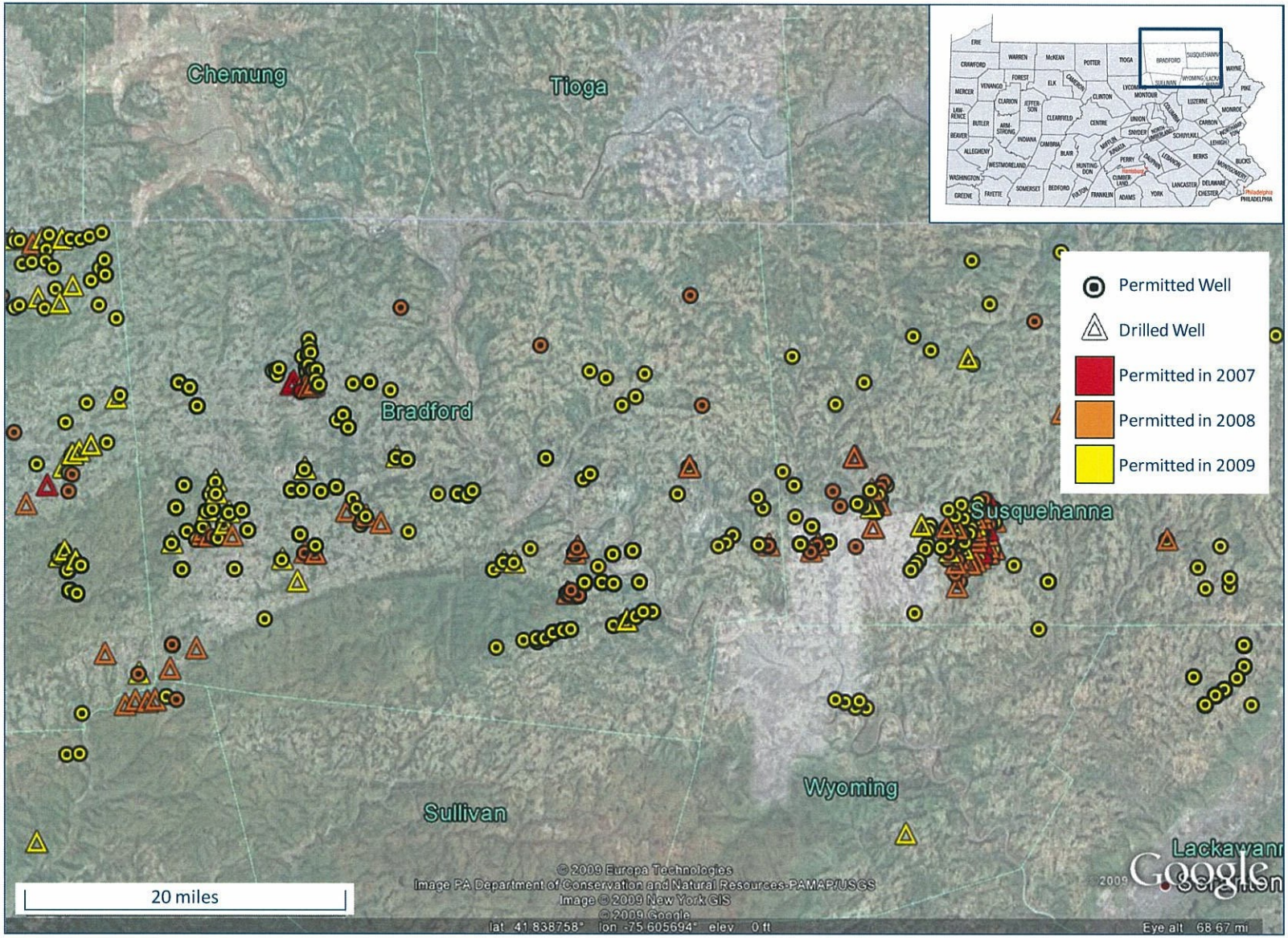

Figure B-8: Well density in the Marcellus formation (Bradford and Susquehanna counties, Penna.), development since 2007[41]

[41] Pennsylvania Department of Environmental Protection Well Data as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09).

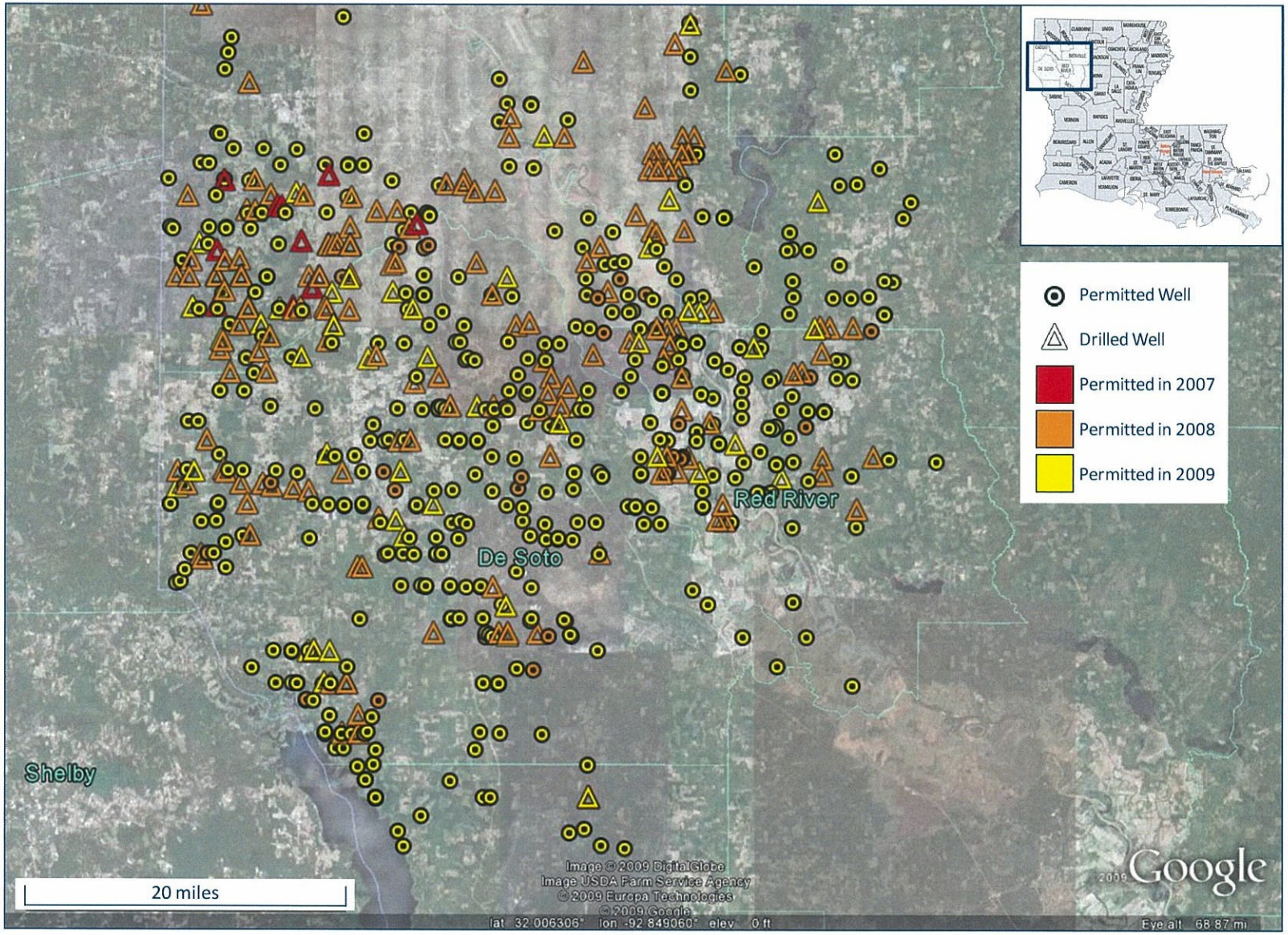

Figure B-9: Well density in the Haynesville formation showing development since 2007[42]

[42] Louisiana Department of Natural Resources SONRIS Well Data as of 10/23/09 (http://dnr.louisiana.gov/haynesvilleshale/haynesville.xls, accessed 11/1/09).

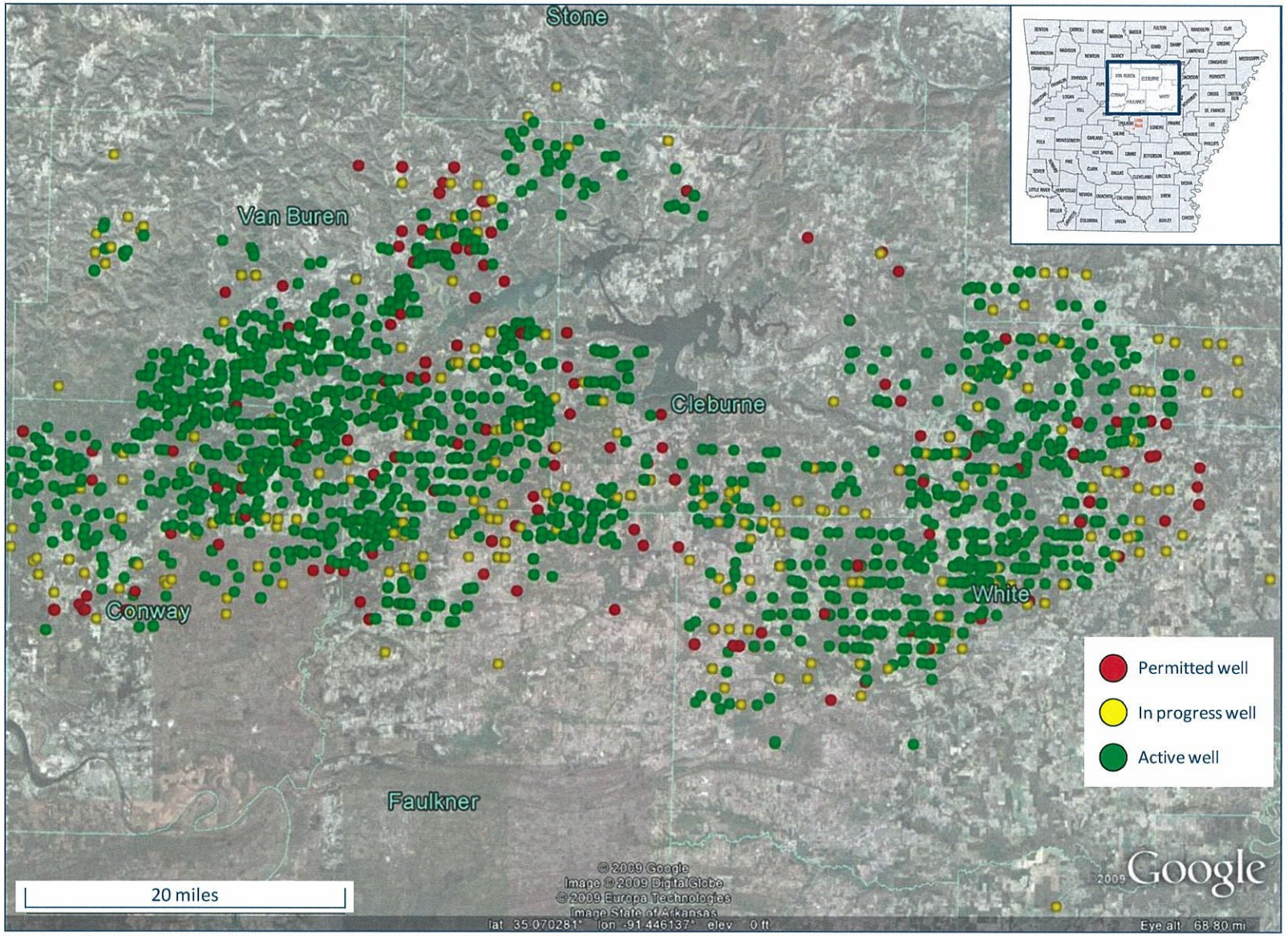

Figure B-10: Well density in the Fayetteville formation showing development since 2004[43]

[43] Arkansas Oil and Gas Commission well data as of 10/22/09 (http://www.aogc.state.ar.us/GIS_GOOGLE/Natural_Gas_and_Oil_Wells.kmz, accessed 11/1/09).

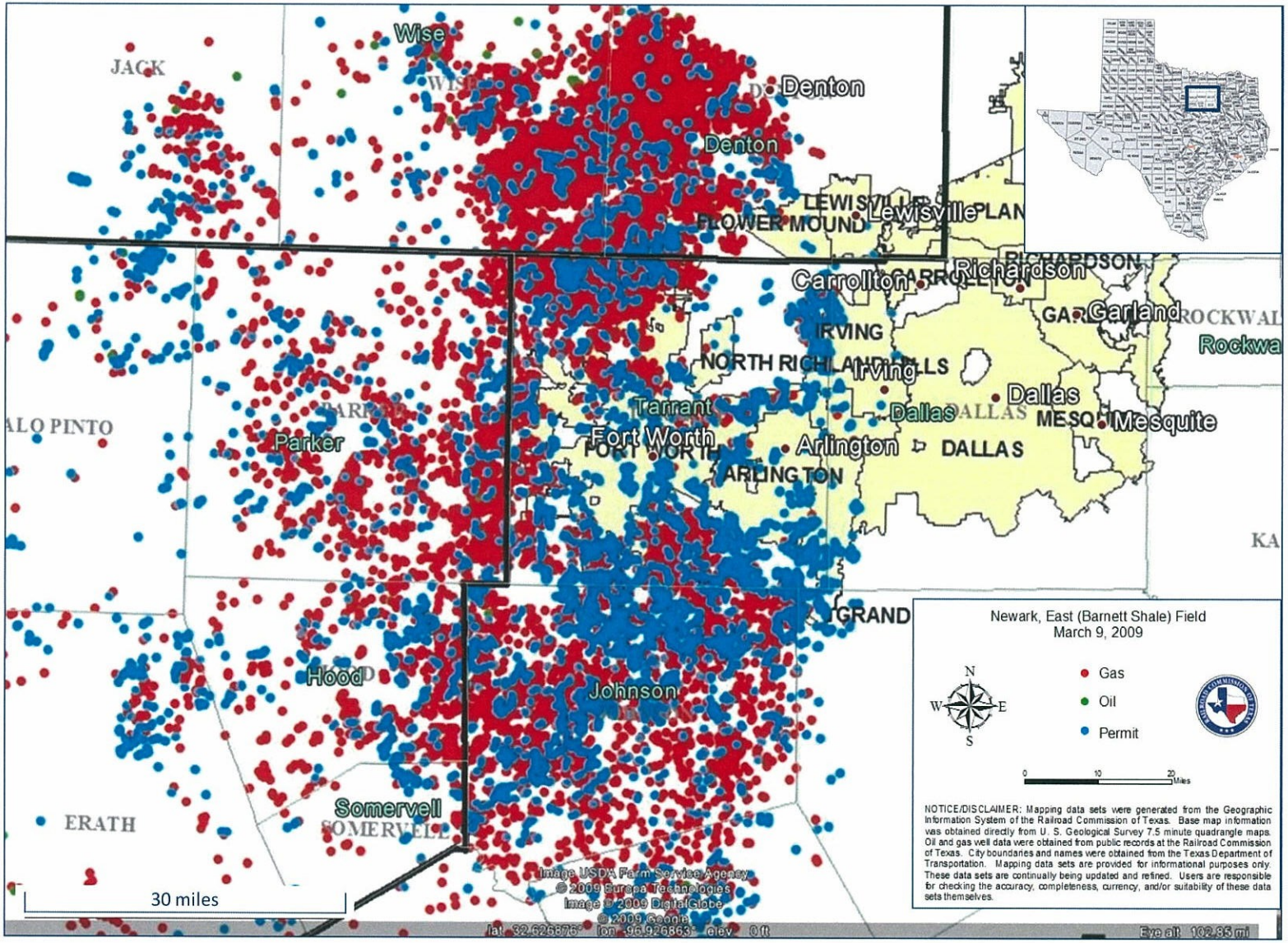

Figure B-11: Well density in the Barnett formation showing development since ~2000[44]

[44] Based on Railroad Commission of Texas image showing density as of 3/9/09 (http://www.rrc.state.tx.us/forms/maps/specialmaps/images/OGM0023.jpg, accessed 11/2/09).

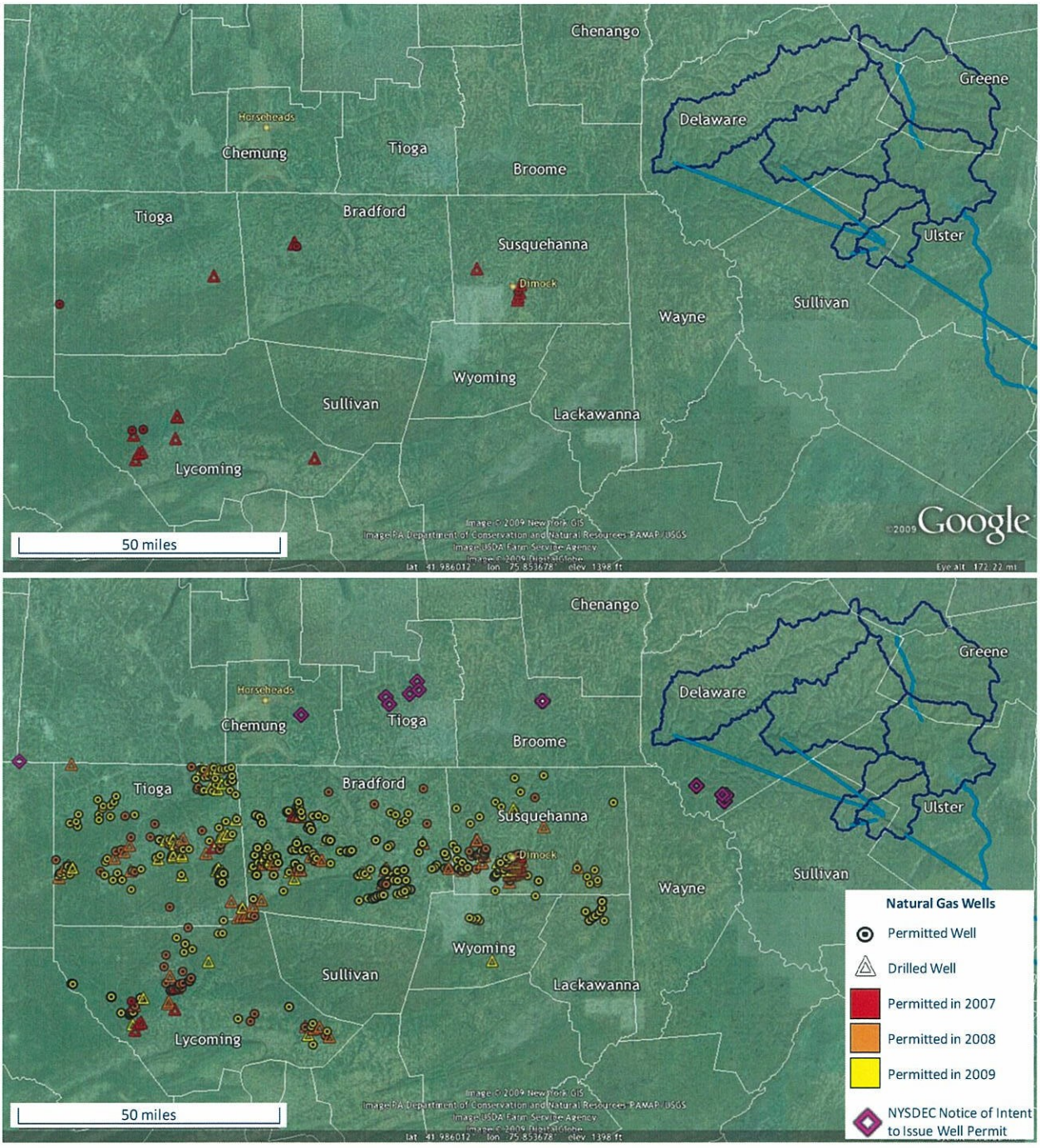

Figure B-12: Marcellus Formation Gas Well Permitting and Completion in New York and Pennsylvania Core Counties in 2007 (Top) and 2009 (Bottom)[45]

[45] Pennsylvania Department of Environmental Protection Well Data as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09). NYSDEC data on Notices of Intent to Issue Well Permits in Spacing Units Which Conform to Statewide Spacing in New York State as of 10/26/2009 (http://www.dec.ny.gov/dmndata/Well_Reports/Unit_Spacing_SW_Rpt.html, accessed 10/27/2009)